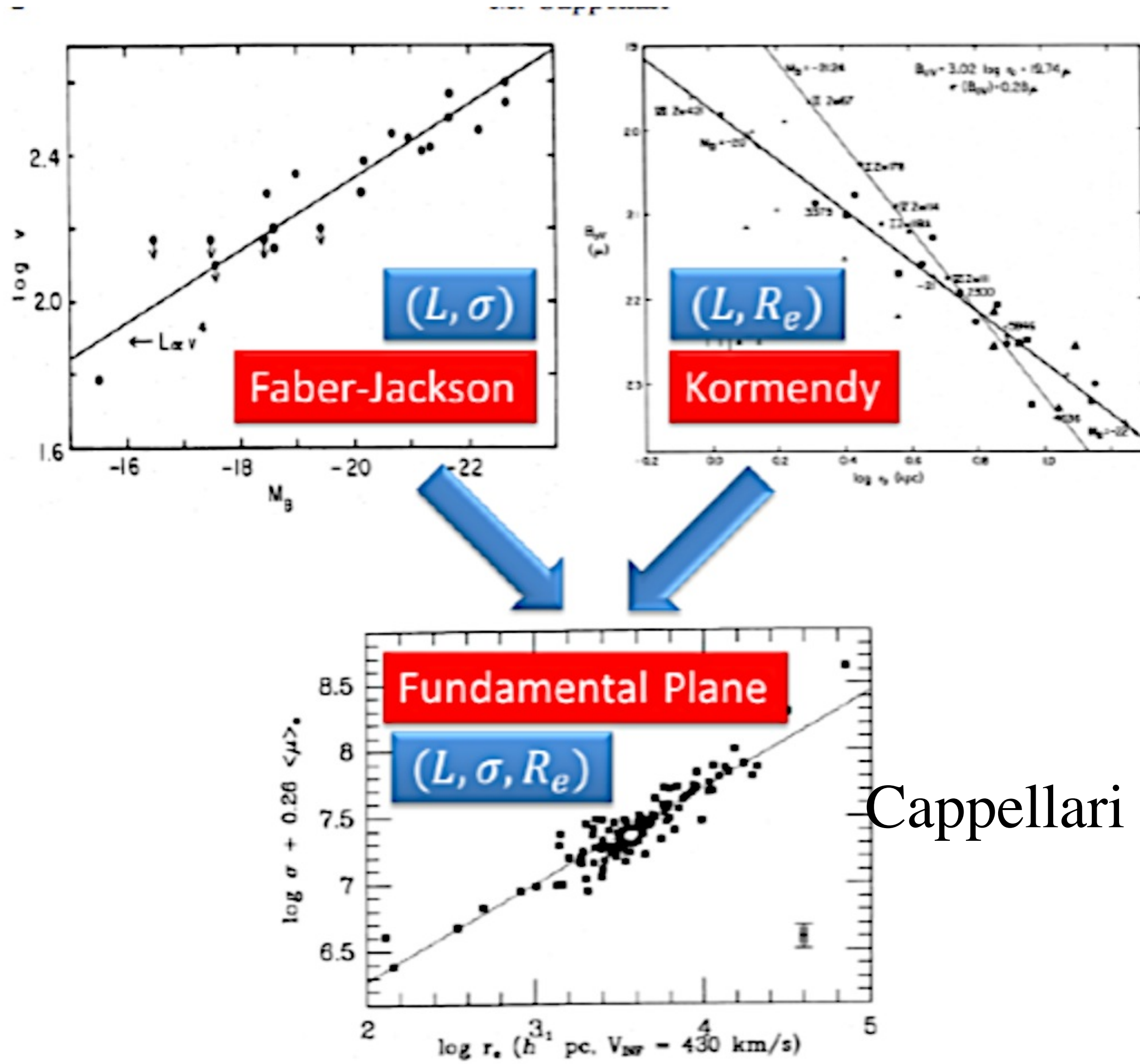
Spheroidal (Elliptical) Galaxies MBW chap 13, S+G ch 6

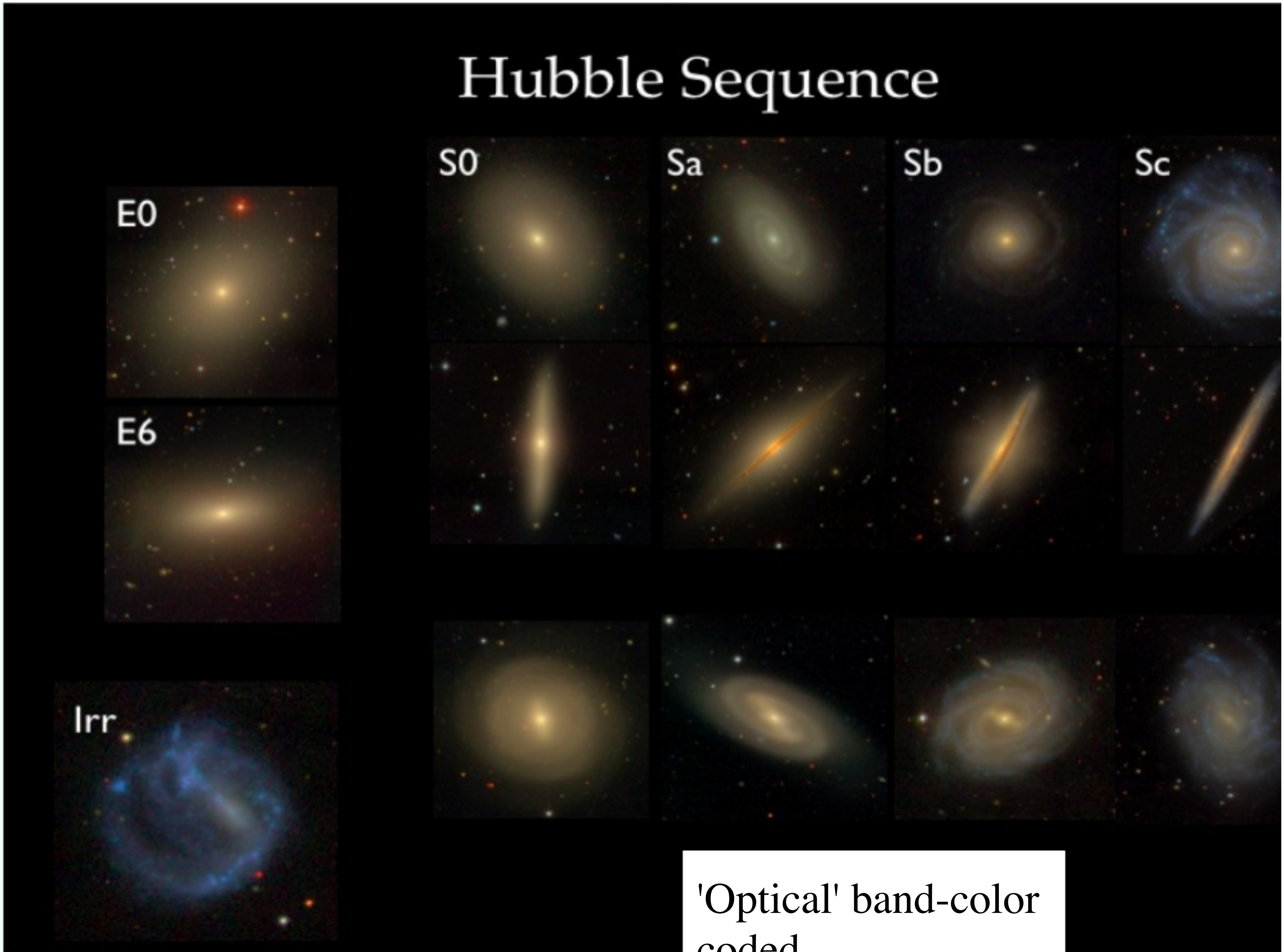
At $M > 10^9 M_\odot$ general properties **fall on the 'fundamental plane'** which includes metallicity, velocity dispersion, size , surface brightness (and some other properties)

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



Cappellari 2014

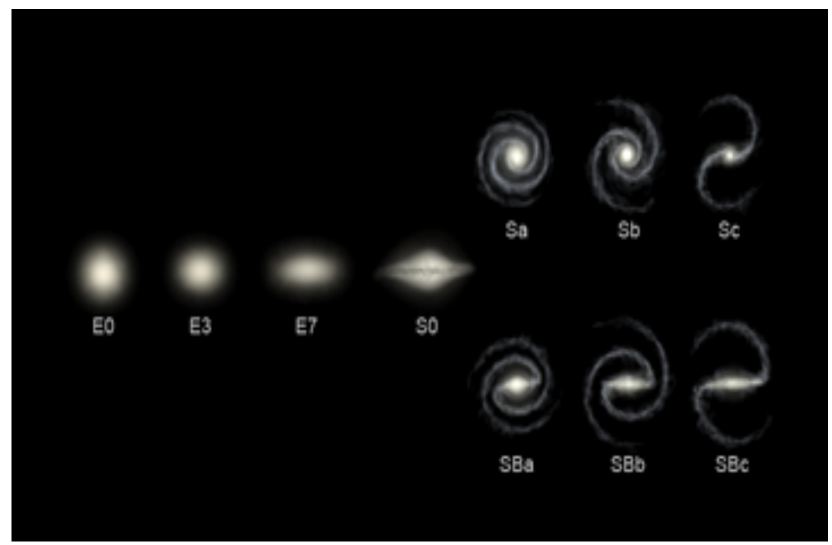
Figure 1. Classic scaling relations. The Faber-Jackson and the Kormendy relations are two special projection of a more fundamental one, aptly named the Fundamental Plane. The three figures are taken from Faber & Jackson (1976), Kormendy (1977) and Djorgovski & Davis (1987) respectively.



'Optical' band-color coded

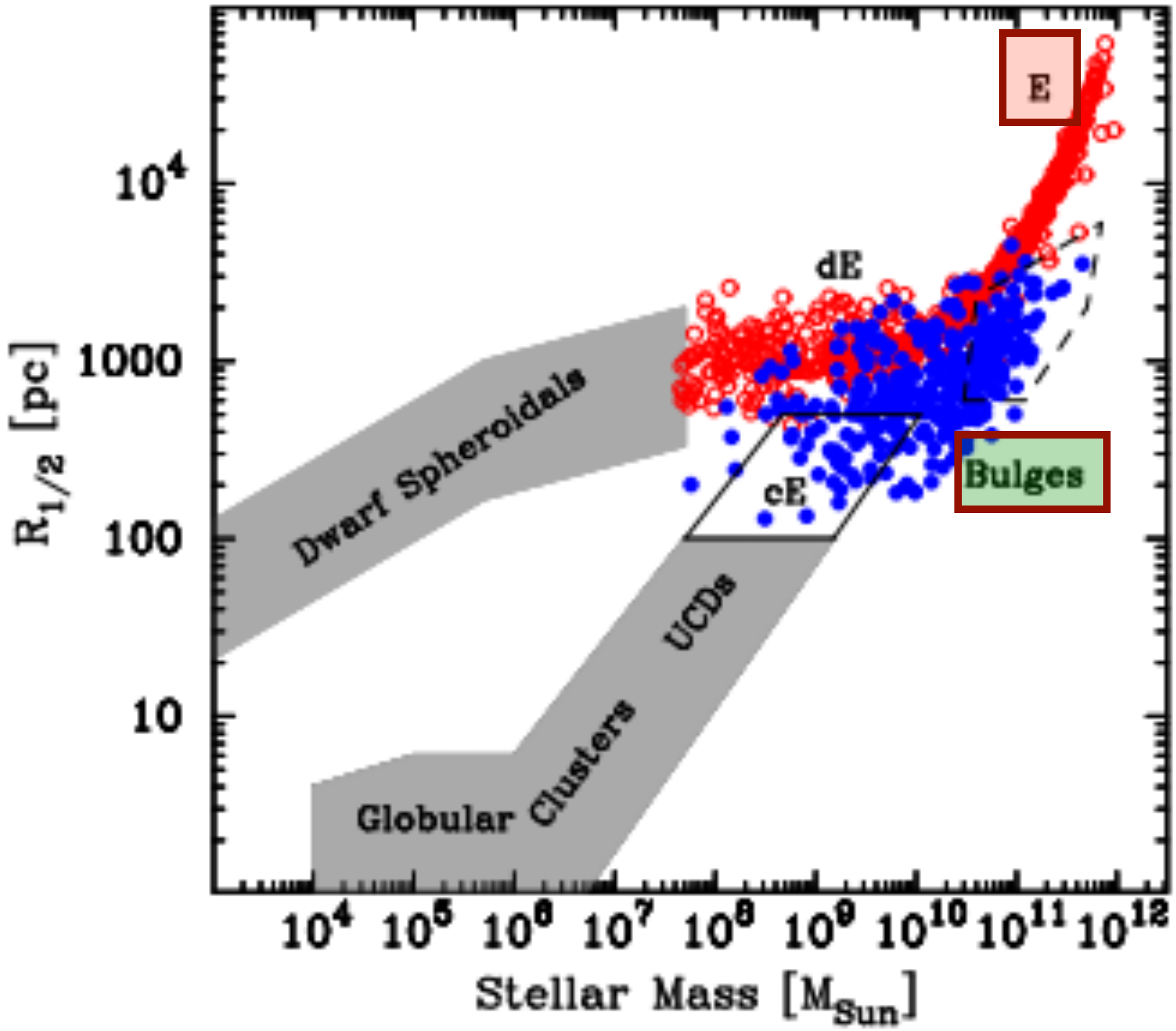
Spheroidal (Elliptical) Galaxies MBW chap 13, S+G ch 6

- Visual Impression: smooth, roundish- deceptively simple appearing- collisionless systems
- While visually 'similar' detailed analysis of spheroids shows 3 categories
  - 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, boxy **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



- 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

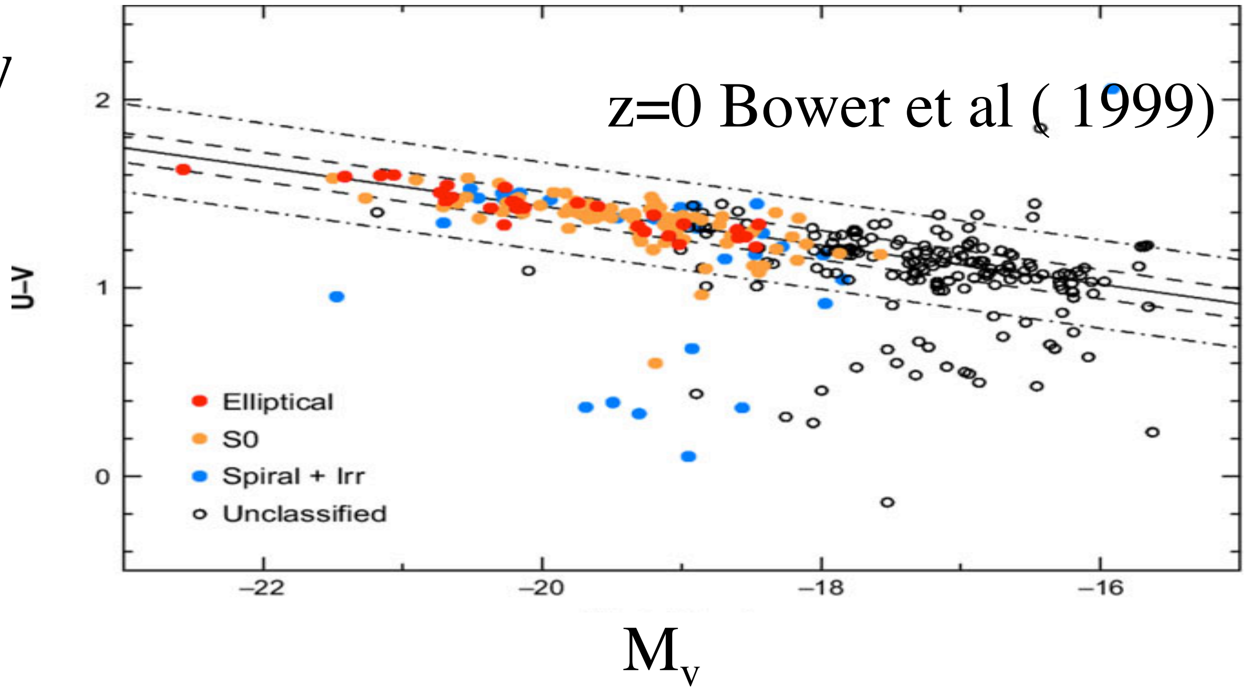


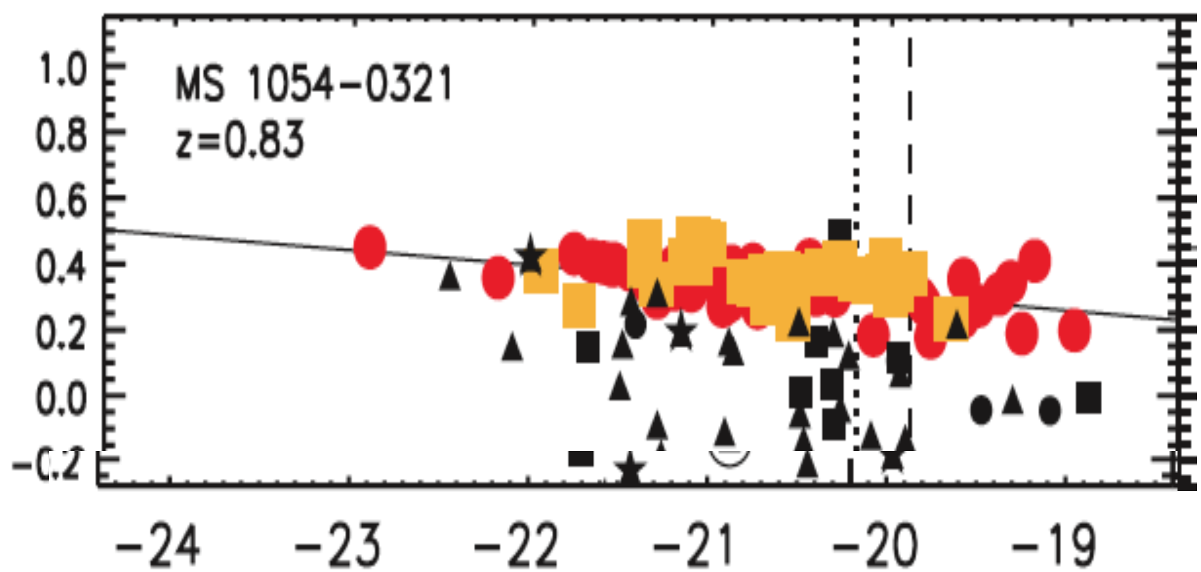
see for more details astr553/Topic07/Lecture_7.html

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

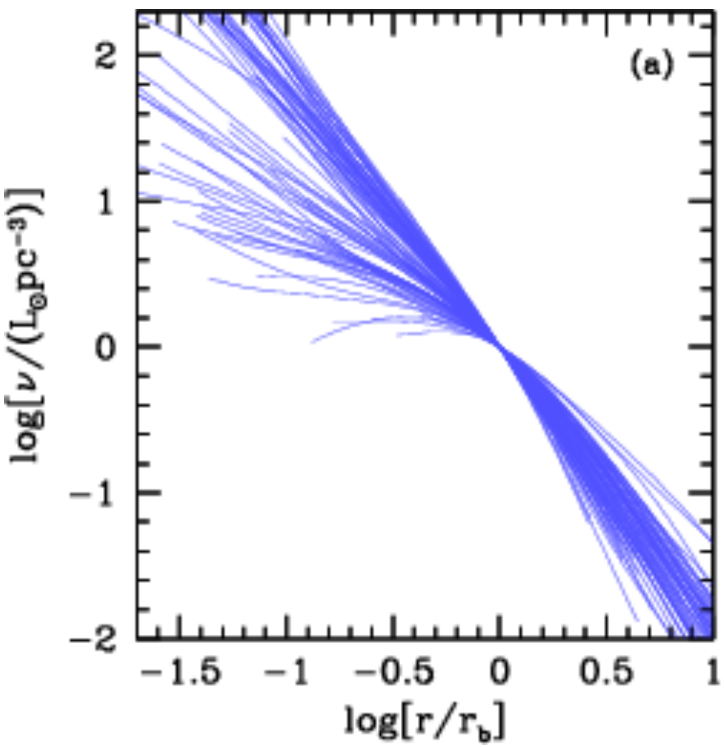


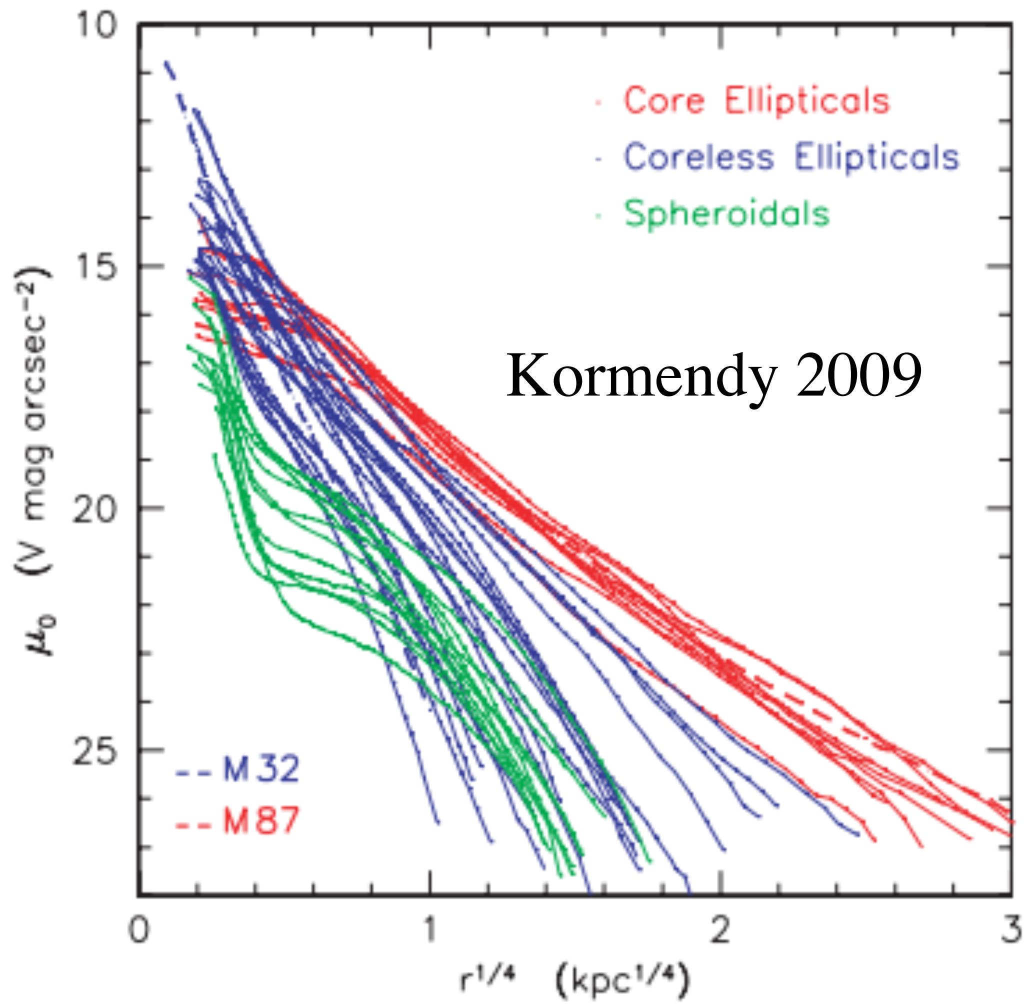


Renzini 2006 ARAA- Stellar population diagnostics of elliptical galaxy formation

Wide Range of Sizes- 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)

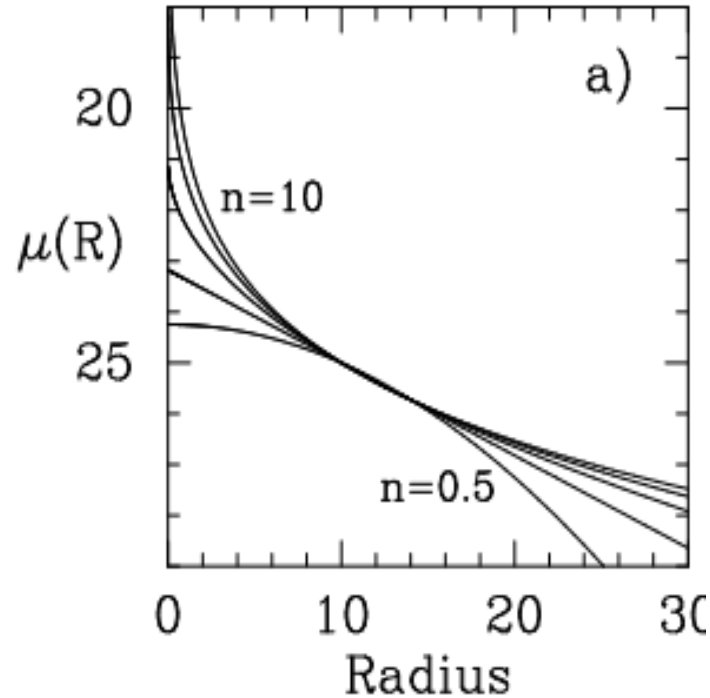




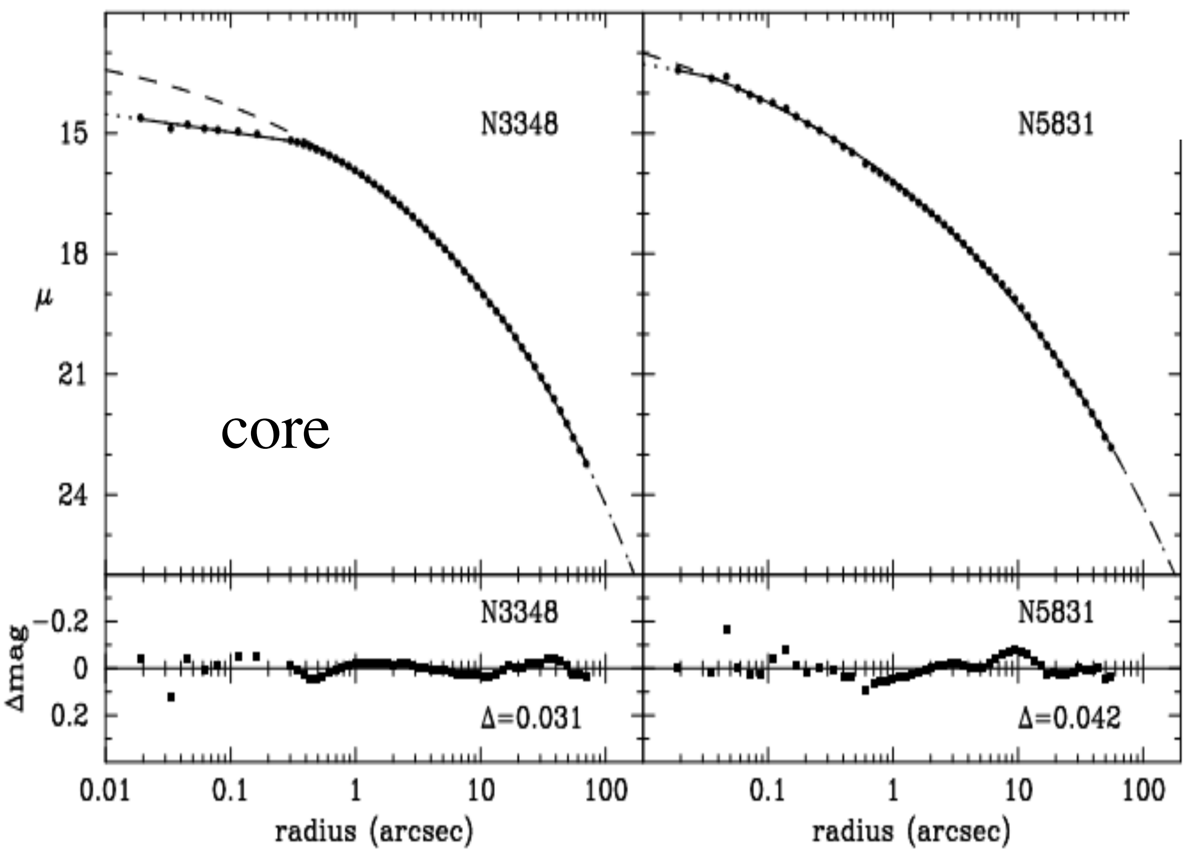
More luminous galaxies tend to have cores, less luminous roughly power law shape in central regions

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)



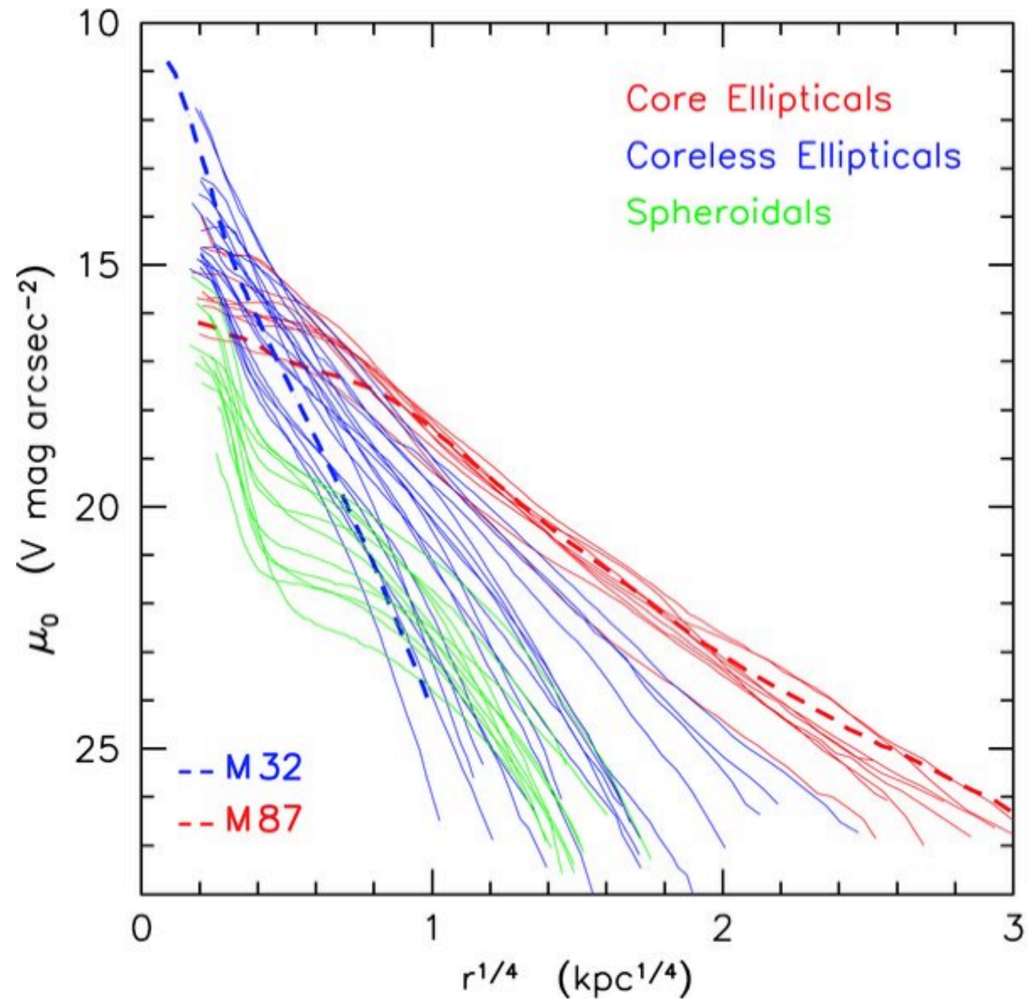
For n=4 (the deV model the total luminosity (S+G problem 6.1) is $7.22pR_e^2$ $I(R_e)$ and half the light comes from within R_e



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)

There are several simple types of mergers

- wet (lots of cold gas)- e.g. spiral x spiral
- dry (little cold gas)- elliptical 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 $n \geq 4$;

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

(8) often contain strong radio sources,

(9) have 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

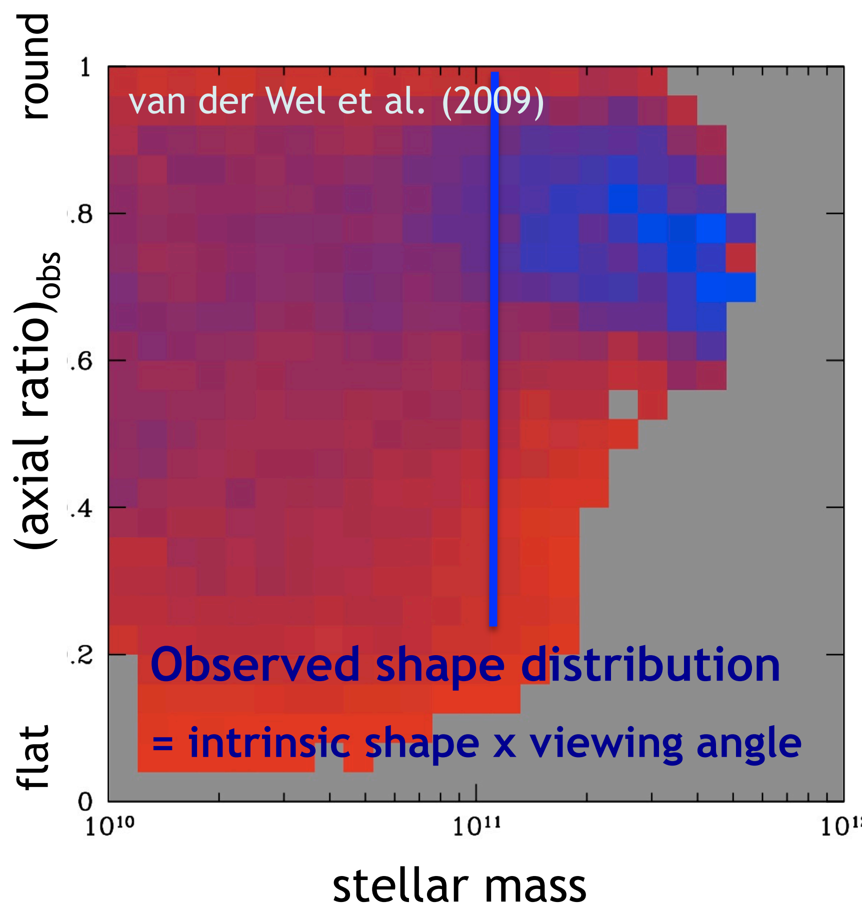
(9) rarely contain X-ray-emitting gas.

The shapes of Early-Type Galaxies

SDSS study of shape distribution of 'passive' (=early type) 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

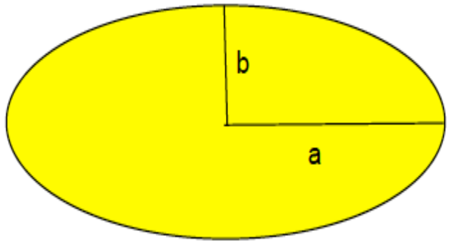


Ellipticals -Shape

- 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

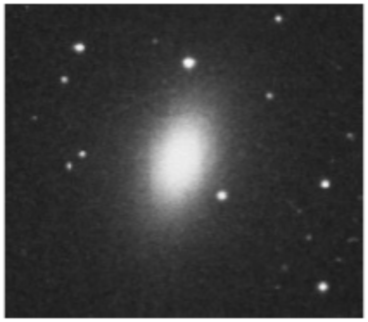
Apparent ellipticity
n=10(a-b)/a
=> En



Observe E0 (round) to E7

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

M87 (E0)

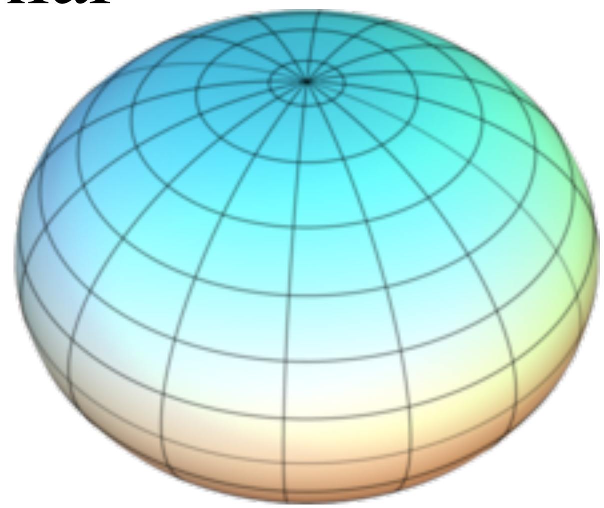


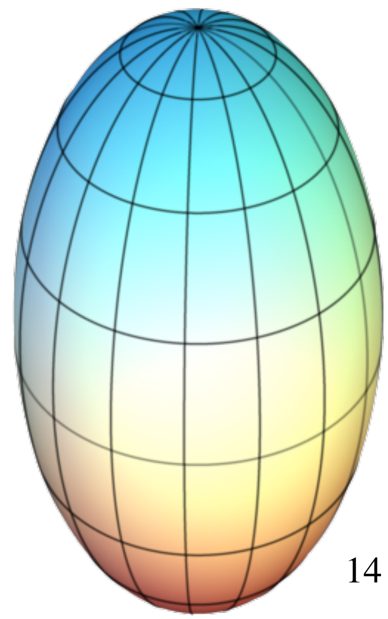
M59 (E5)

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

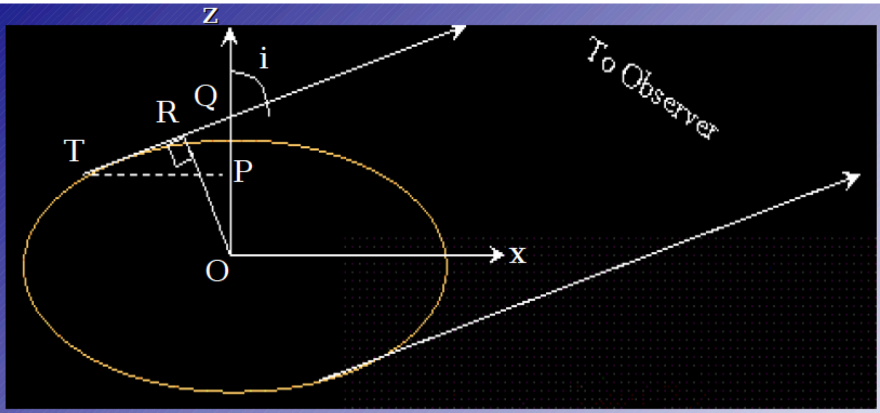
- Shape alone cannot tell us what is going on
- Triaxial ellipsoids:
  - $[x^2/a^2]+[y^2/b]^2+[z^2/c^2] = 1$
- From morphology alone can't tell if elliptical galaxies are

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

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

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

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

Triaxiality $r(m); m = x^2 + y^2/p^2 + z^2/q^2$

D.Davis

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

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

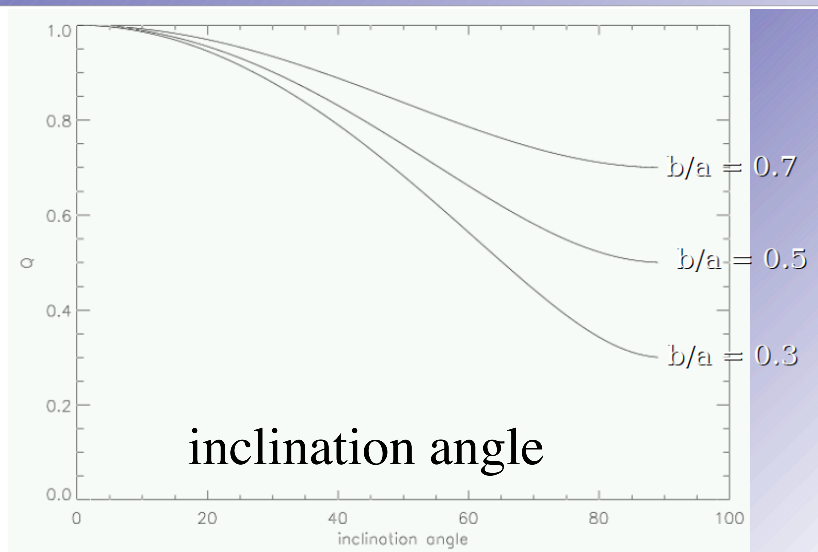
Using our definition of m for the last step. Finally we can rewrite this as

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

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

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

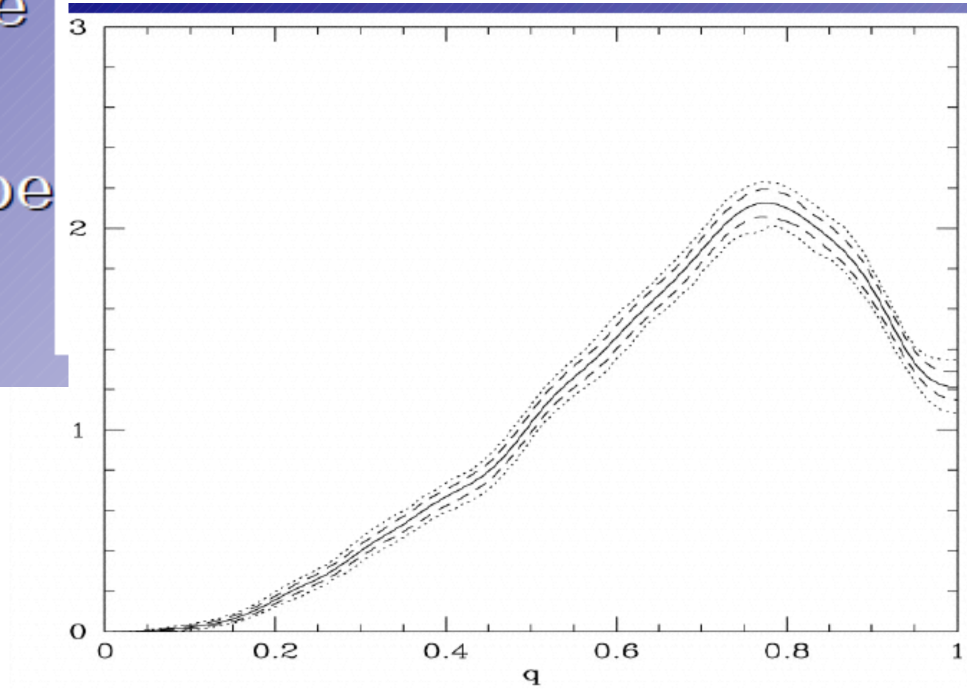
q



inclination angle

Ellipticals are Triaxial

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



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

Shape could also be due to rotation around z axis.

Density Profile

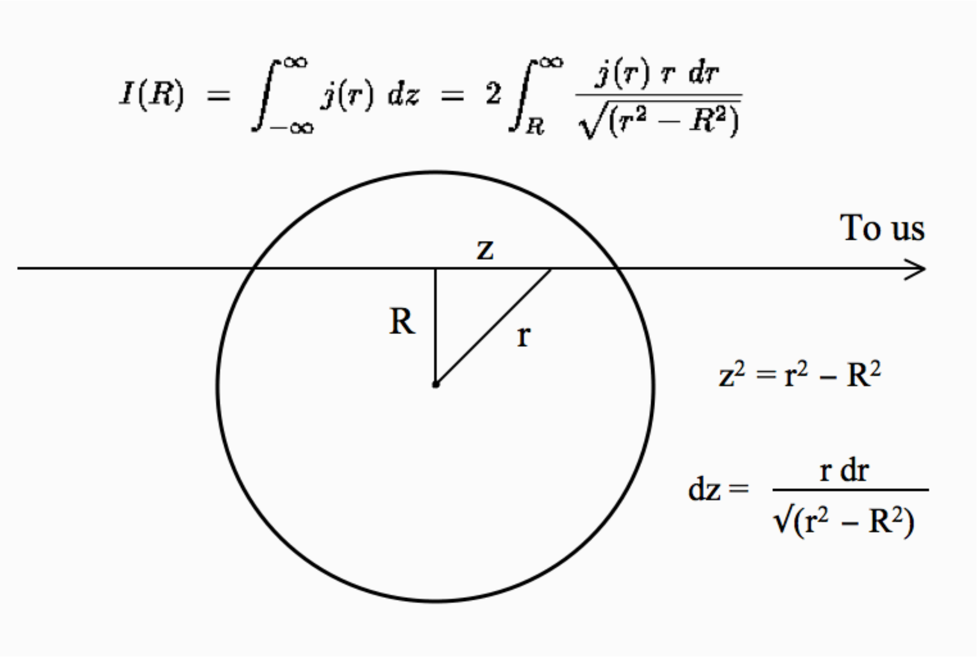
- I(R) is the projected luminosity surface brightness, j(r) is the 3-D luminosity density (circular images- if image is elliptical no general solution)

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

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

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

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



While the Sersic model is a better fit to the surface brightness profiles it is not easily invertable 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 $r_c=3\sigma/\mathrm{sqrt}(4\pi G p_c)$

Ages of Elliptical Galaxies

- Using optical spectra there is an age-metallicity degeneracy
- This can be broken (to some extent) via us of IR data and by measuring galaxies at higher redshifts
- Analysis (van Dokkum and van der Maerl 2007) indicates consistency with 'passive' evolution (no star formation for a long time) and a formation redshift ~2 (depends on the IMF) for the stars- **not clear when the galaxies formed**
  - theory/observations indicate that ellipticals formed from mergers and thus the age of the galaxy and the stars differs.

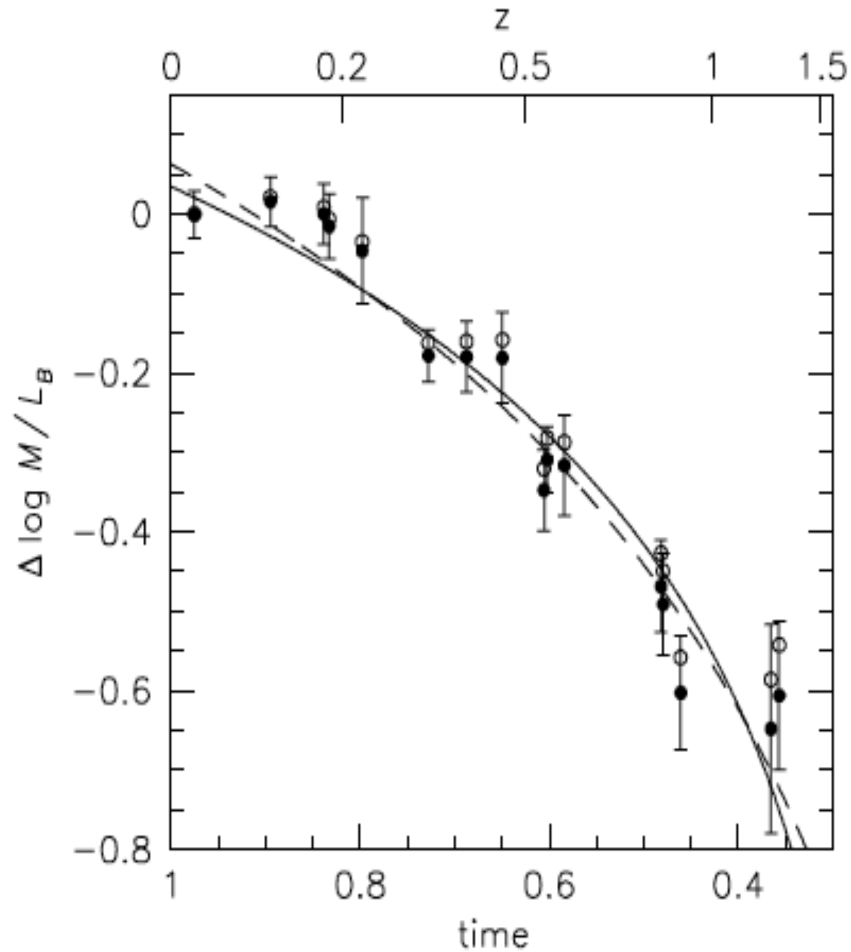
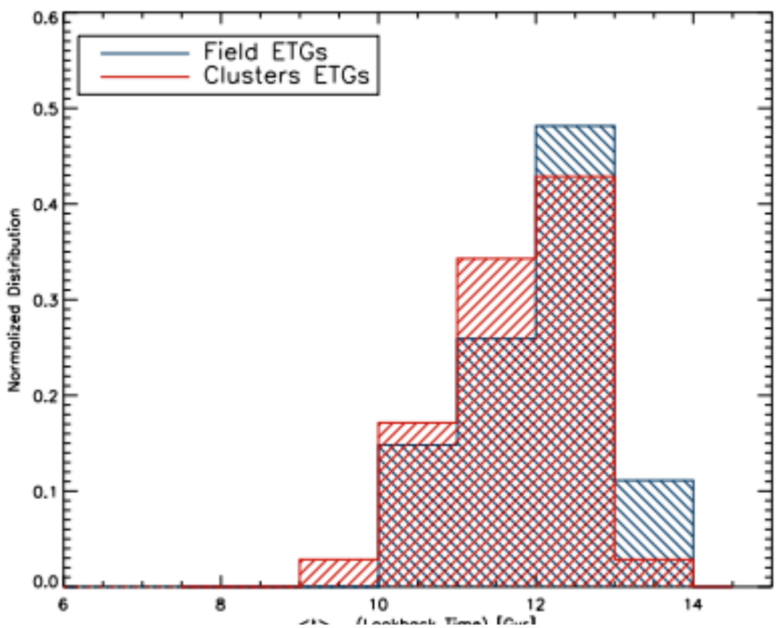


FIG. 8.— Evolution of the mean M/L_B ratio of massive cluster galaxies with time. Open symbols are the same datapoints as shown in Fig. 6. Solid symbols with errorbars are offset by $-0.05 \times z$ to account for progenitor bias (see text). The solid line shows the best fitting model for a Salpeter-like IMF, which has a formation redshift of the stars $z_* = 2.01$. The broken line shows a model with a top-heavy IMF (slope $x = 0$) and a formation redshift $z_* = 4.0$ (see § 7).

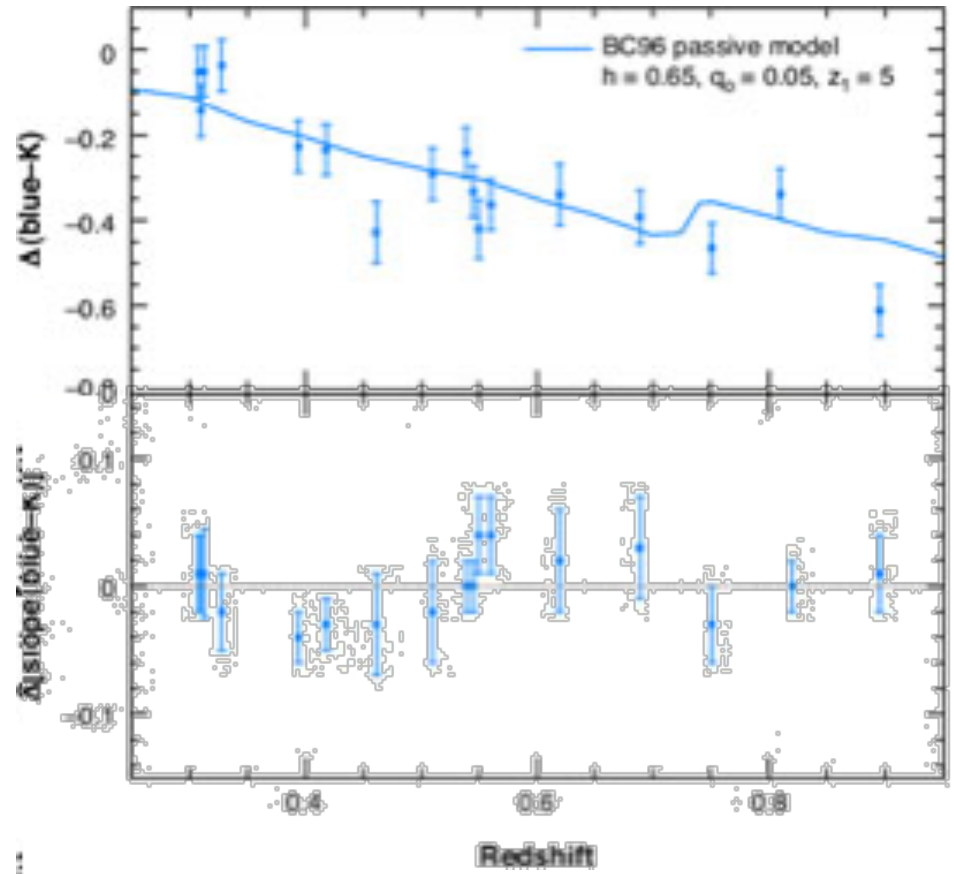
Higher z observations constraint on origin

- At higher z massive elliptical galaxies in clusters have colors and luminosities (at z<1.2) consistent with 'passive' evolution e.g. galaxy forms at higher z and does not change with time and stars 'just evolve'- a SSP (!)



6 8 10 12 14

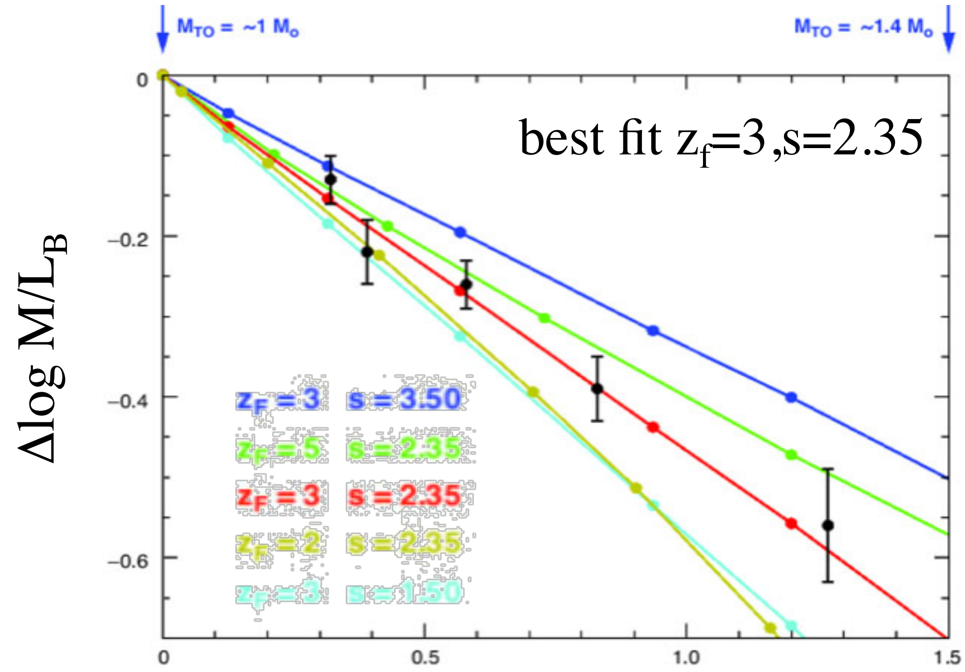
look back time of star formation (gyrs)

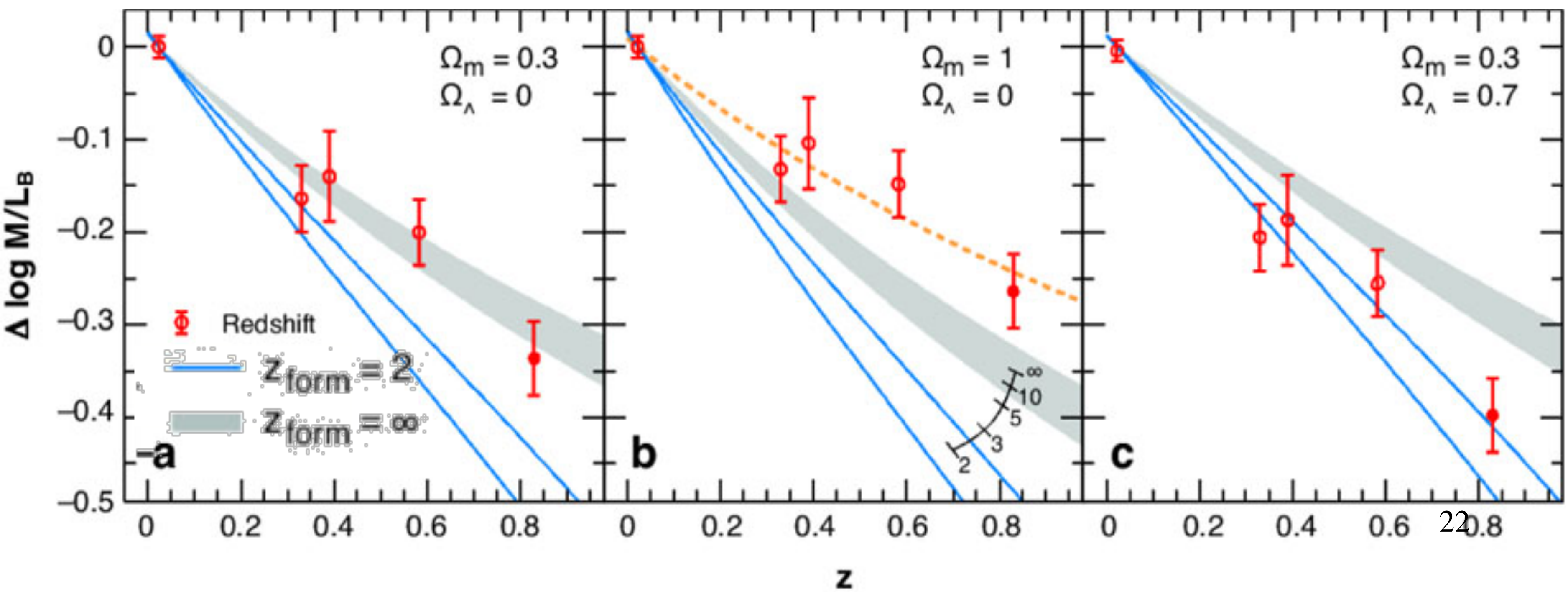


using the consistency of the colors of these galaxies with 'passive' evolution the ages of massive ellipticals in clusters is ~10-13Gyr (!)- Rettura et al 2012

Evolution of Elliptical Galaxies

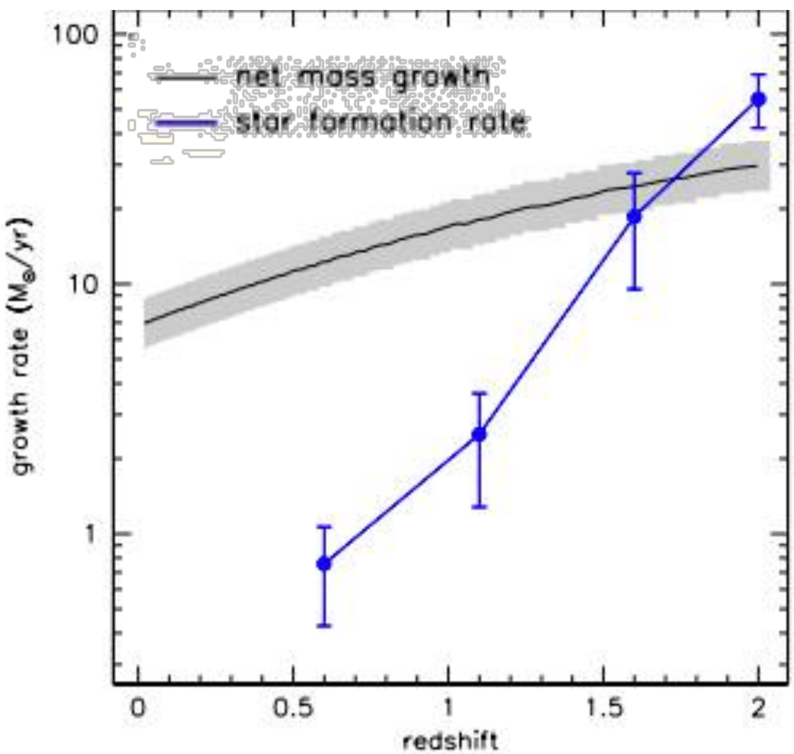
- 'age date' the galaxies with higher redshift observations
- The evolution with redshift of the M_* / L_B ratio of simple stellar populations of solar metallicity and various initial mass function slopes and formation redshifts:

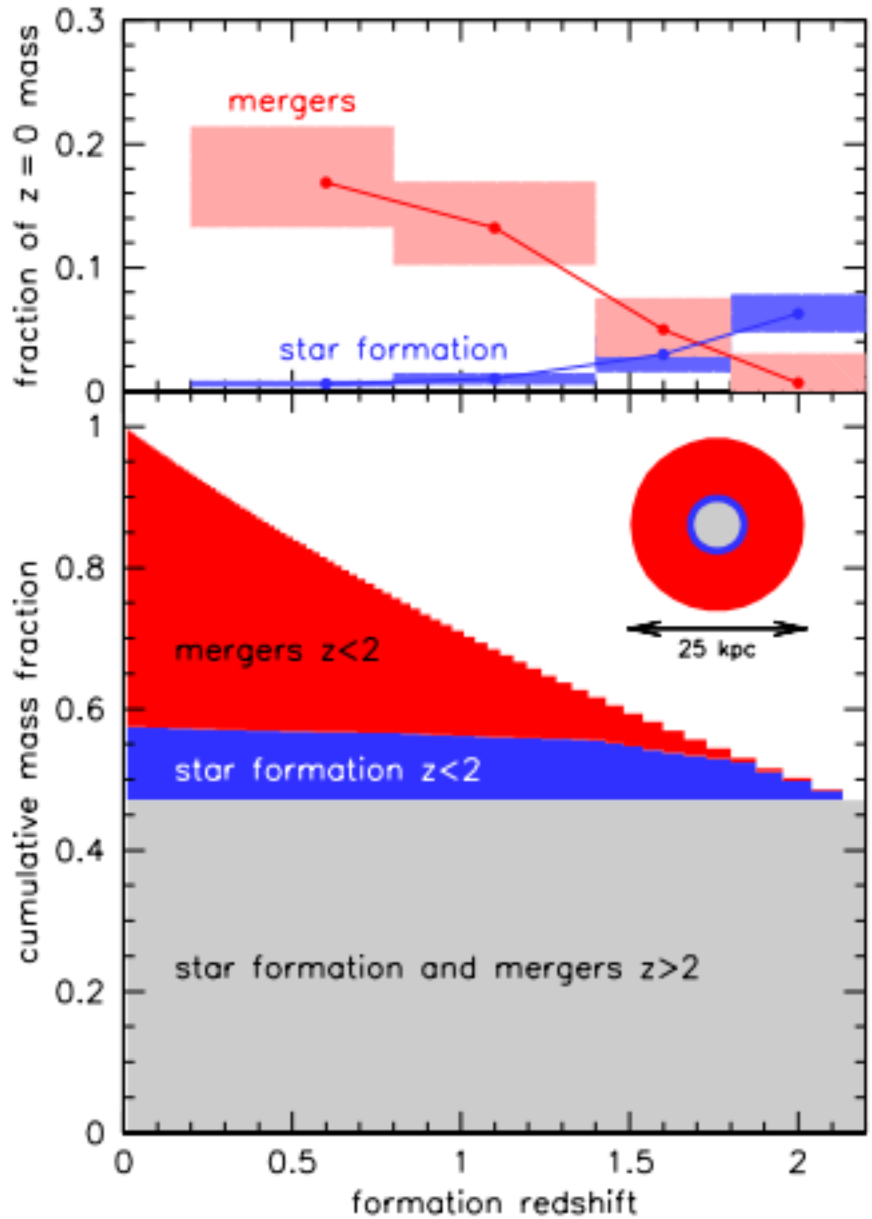




Growth of Elliptical Galaxies

- Massive elliptical galaxies had lots of star formation at high (z>1.5) redshift but more or less stopped forming stars at more recent times
- Growth in E galaxy mass z<2 has been primarily via mergers- this is also consistent with chemical abundance gradients (but the merging galaxies are not the same as systems today; everything evolves)

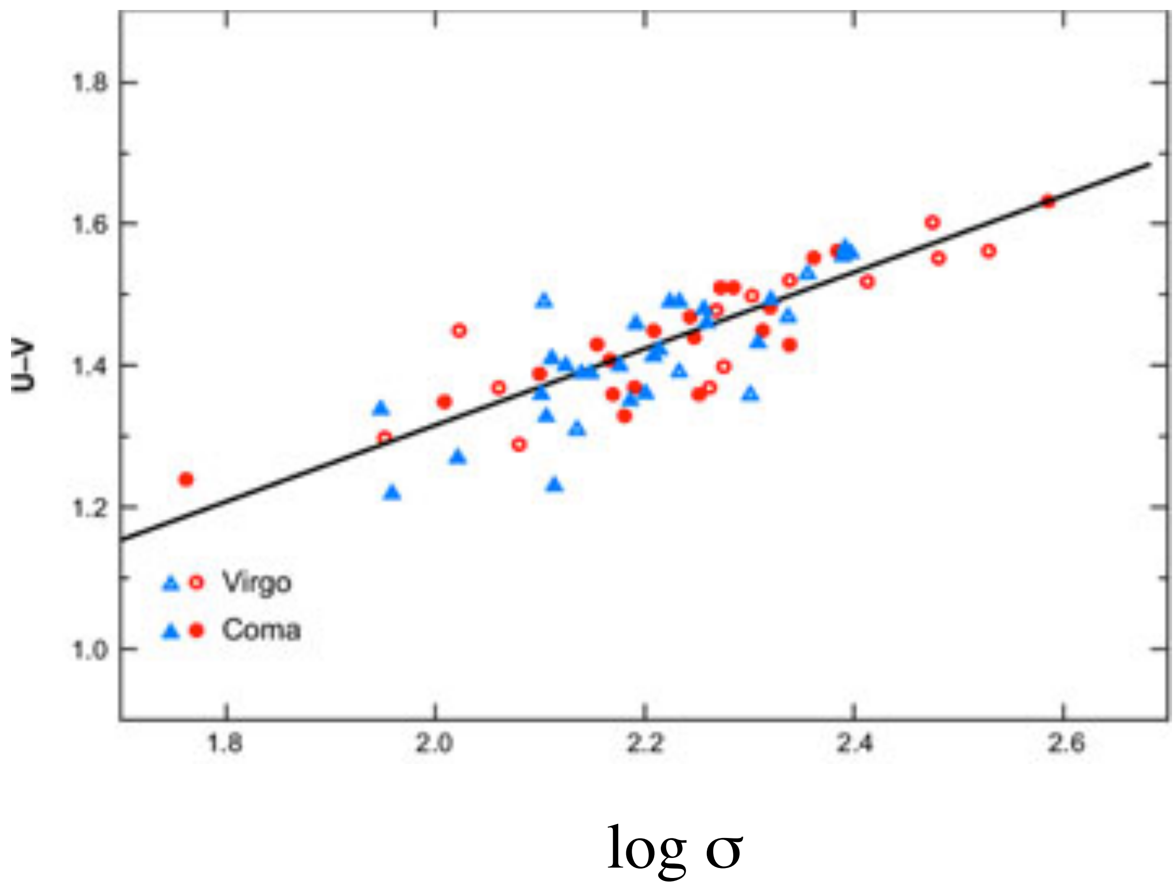




van Dokkum et al 2010

Color - Velocity Dispersion

- Strong relation of color and velocity dispersion- a projection of the *fundamental plane* where velocity, size, luminosity strongly correlated
- the color- velocity dispersion relation strongly constrains 'dry' mergers since merging without star formation increases mass (related to σ via the virial theorm), but leaves colors unchanged,



Bower, Lucy, Ellis 1991

Elliptical Galaxies So Far

- Visual Impression: smooth, roundish- *deceptively* simple appearing- collisionless systems
- Galaxies are very old
- Strong correlations of many properties: size, surface brightness, metallicity, velocity dispersion,color, luminosity
- Effect of viewing geometry on shape, projection effect - inversion of surface brightness profiles to density (Abel integral, in general non-analytic)
- Surface brightness profiles fit by 'Sersic' law, 3 free parameters (n, I(0), R_e)
- **See chapter 13 in MBW for lots of information !**

Final Exam and Project

Final

Friday Dec 20   10:30 am - 12:30 pm   CSS 0201

- This is the date on the University schedule: we **can** change it if the class desires

deadline for project Dec 4

Summary-2 Kinds of Ellipticals

Star are not relaxed:E galaxies retain a lot of the details related to their origin

How to get this information!

Notice correlation of dynamical properties and morphology

Giant ellipticals

essentially non-rotating

anisotropic and triaxial

more 'circular'

have cores

large Sersic indices

Low Luminosity Ellipticals

more rotation supported

isotropic oblate flattened spheroids

'coreless'- power law inner slopes

smaller Sersic indices

The most massive systems

- 'cD' (central dominant) galaxies lie only at the centers of groups and clusters- not all brightest cluster galaxies (BCGs) are cDs.
- Their surface brightness profiles are very extended and they often have very rich populations of globular clusters. Quite spheroidal shape.
- X-ray emission in clusters is centered on them.