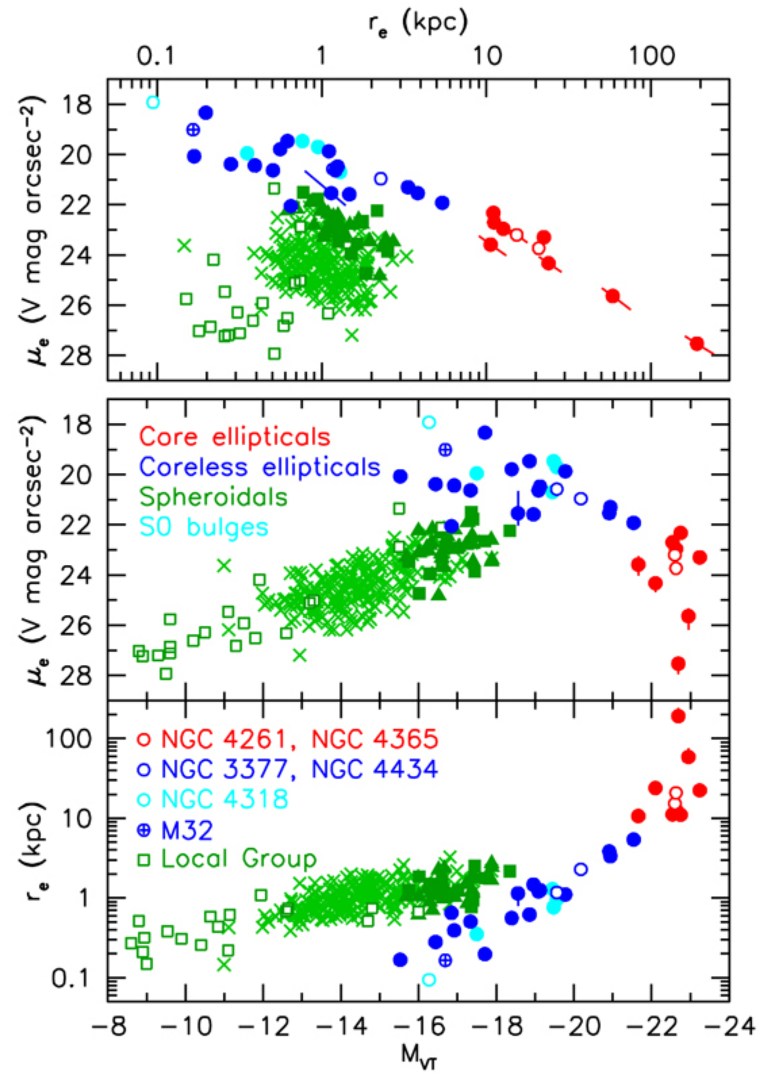
Spheroidal (Elliptical) Galaxies MBW chap 13, S+G ch 6

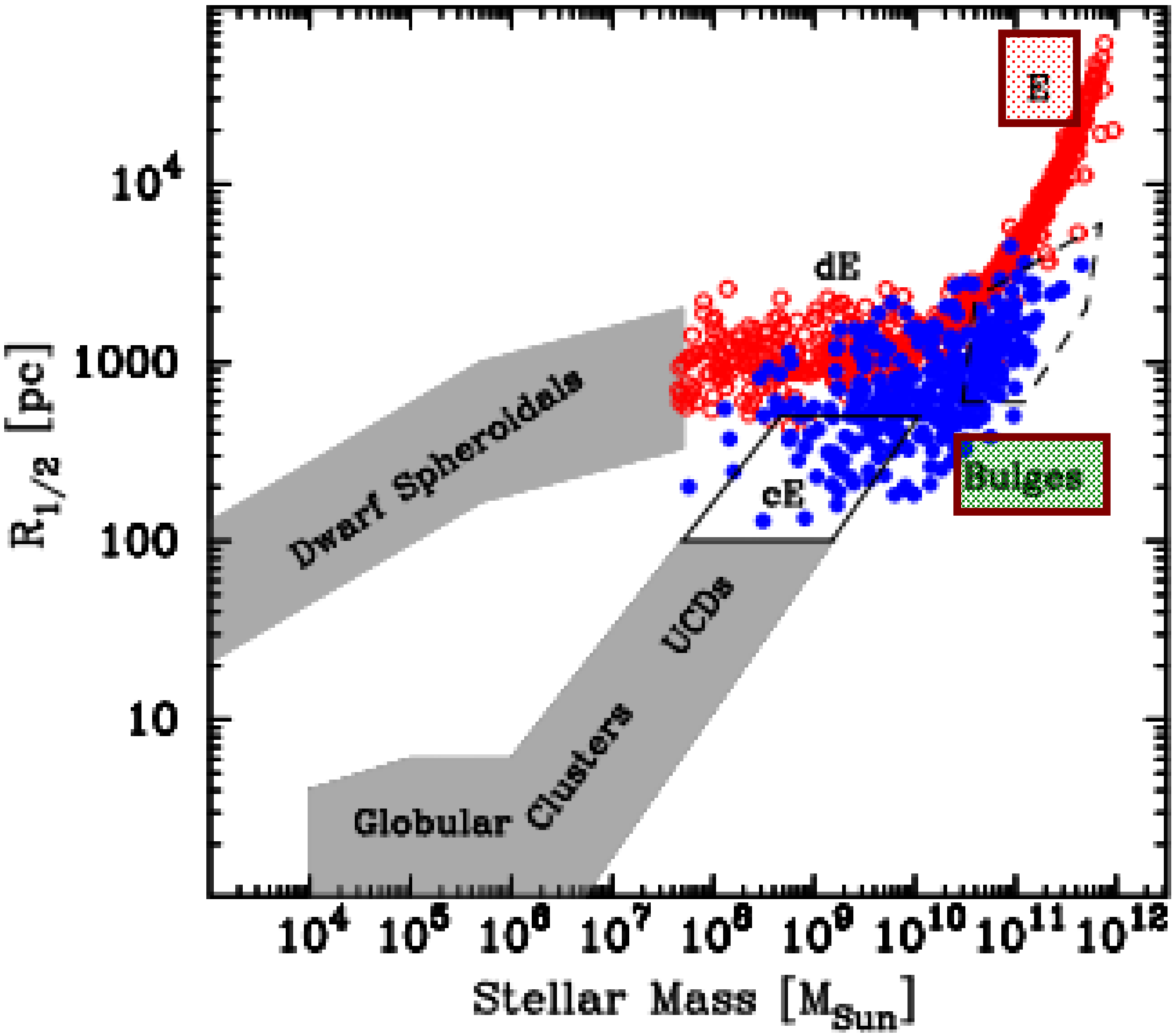
- Visual Impression: smooth, roundish- deceptively simple appearing- collisionless systems
- While visually 'similar' detailed analysis of spheroids groups them into 3 categories
  - Massive/luminous systems: little rotation or cool gas, flat central brightness distribution (cores), triaxial; lots of 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
- 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



Absolute M

- 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 modesl for the surface brightness distribution

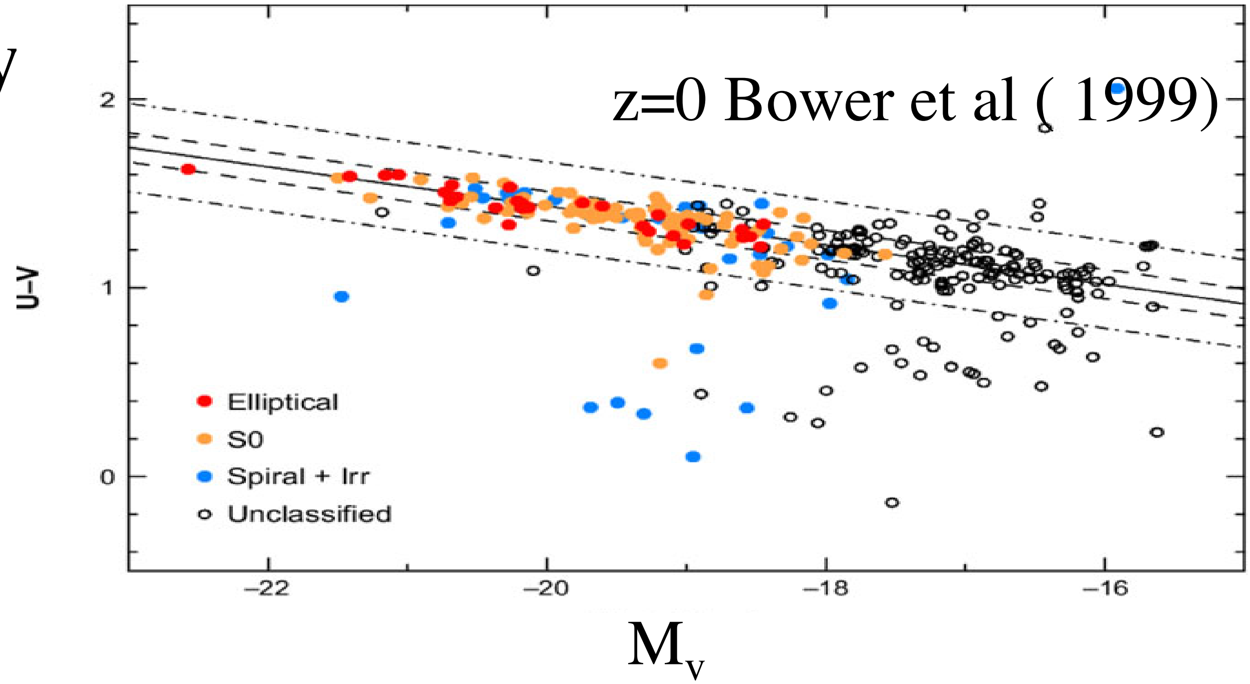


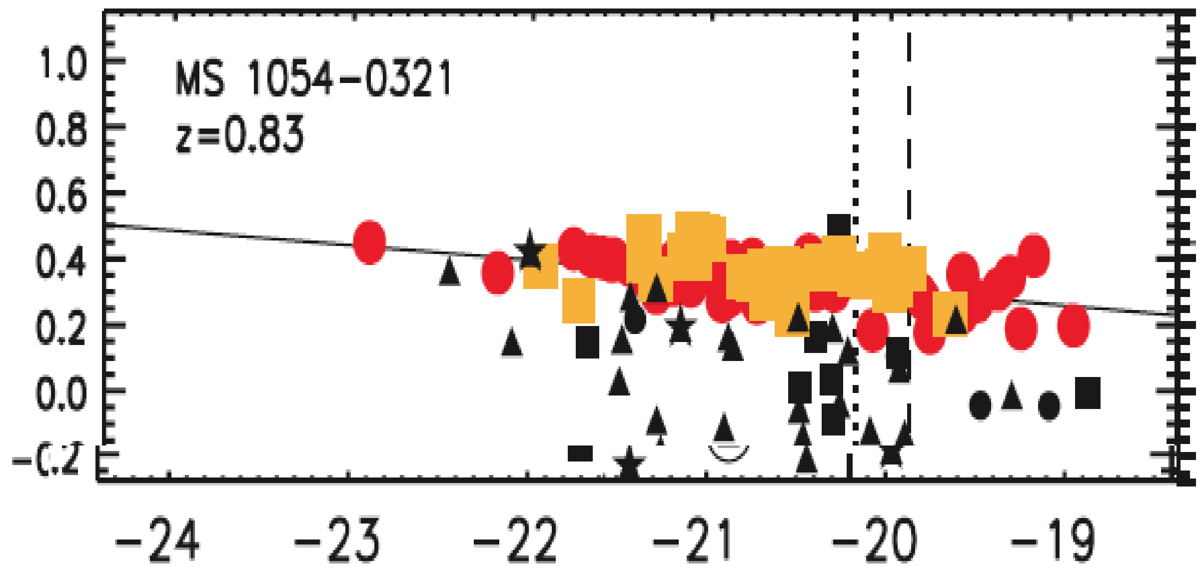
Graham 2012

[see for more details astr553/Topic07/Lecture_7.html](astr553/Topic07/Lecture_7.html)

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

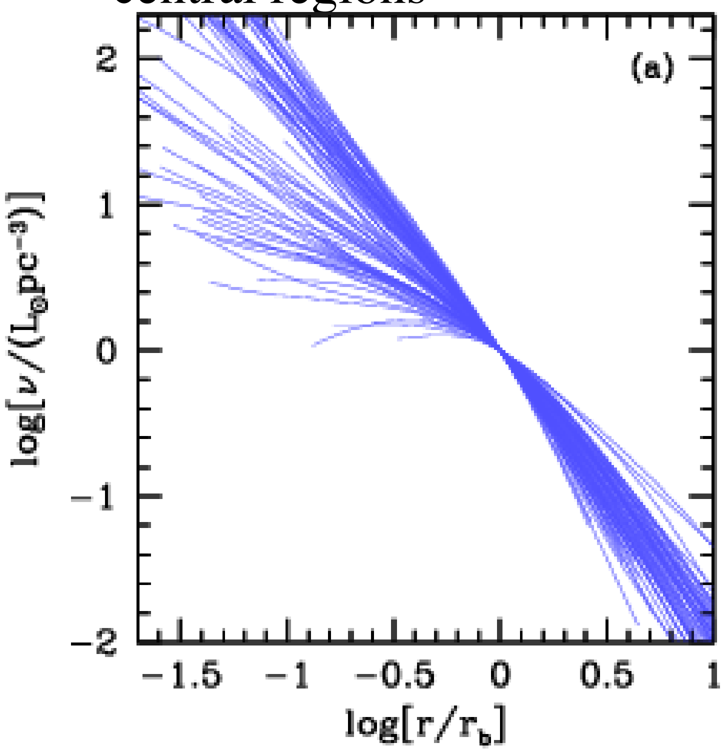


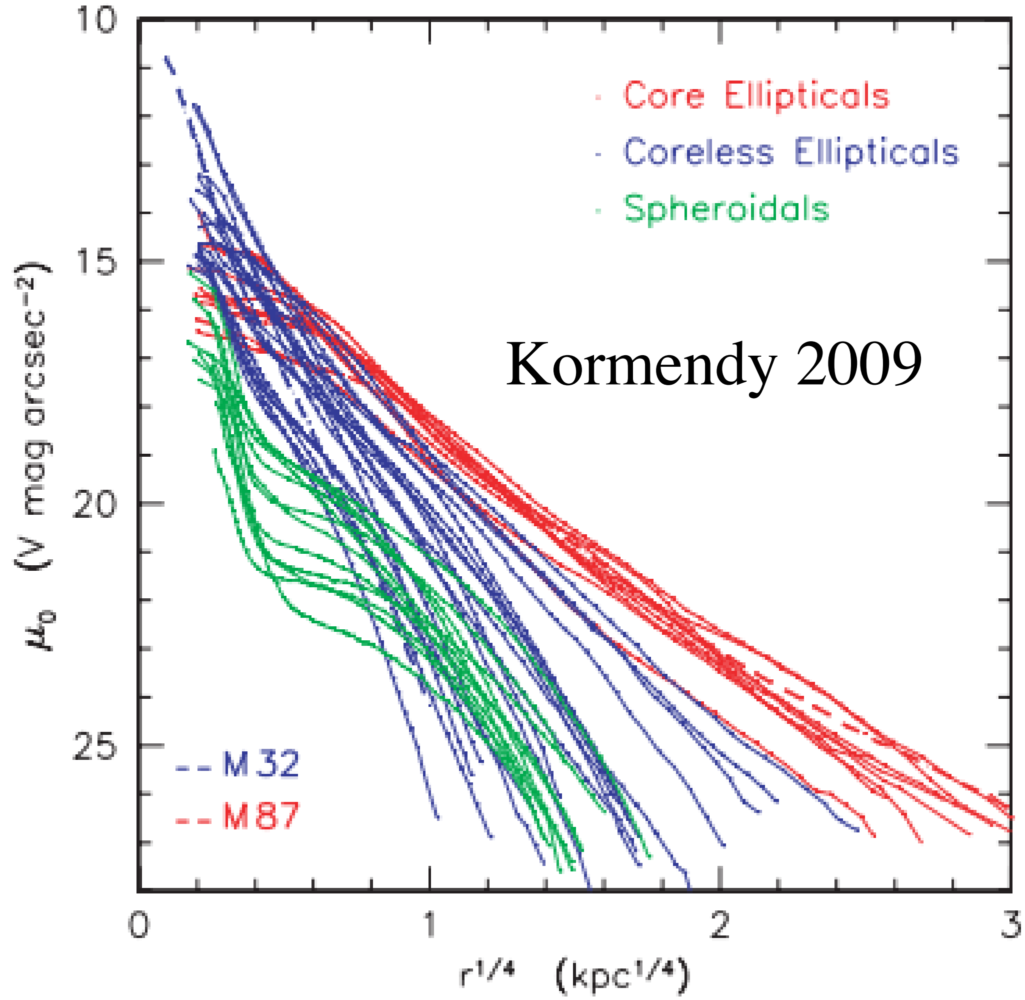


Renzini 2006 ARAA- Stellar population diagnostics of elliptical galaxy formation

Wide Range of Sizes- But Homologous

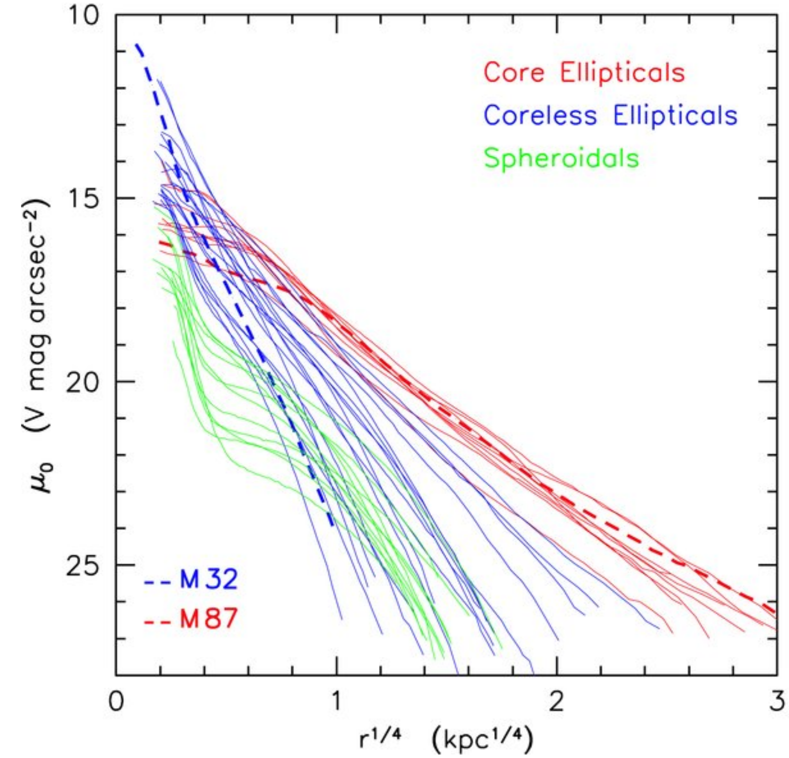
- the family of spheroids can usually be well fit by the Sersic model, but there are some deviations in the centers (cores and cusps)
- More luminous galaxies tend to have cores, less luminous roughly power law shape in central regions

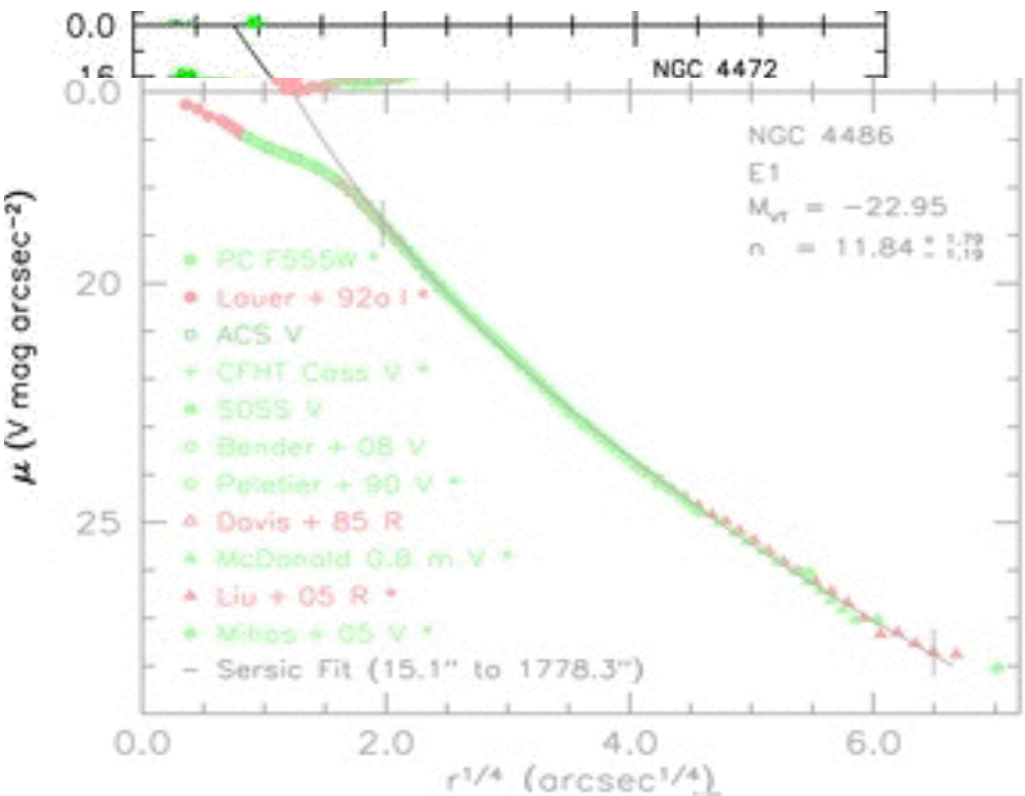




Surface Brightness Distribution of 2 Giant E Galaxies

- Except for core these 2 systems have very similar profiles





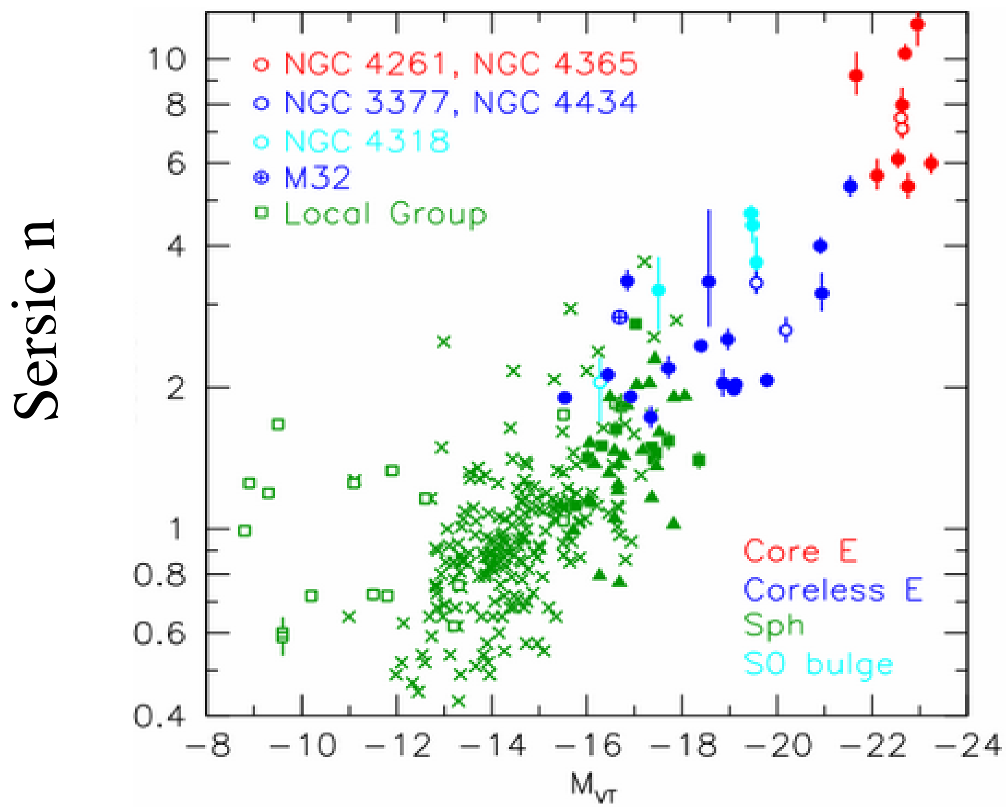
Why Interesting

- 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

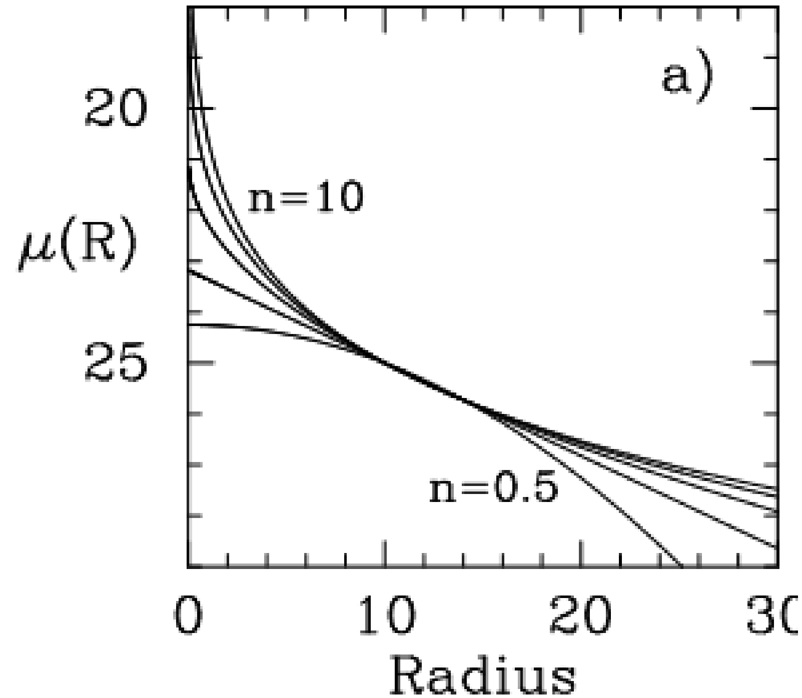
- •wet (lots of cold gas)- e.g. spiral x spiral
- •dry (little cold gas)- elliptical x elliptical
- •wide range of mass (dwarf into normal)
- •narrow range - mass ratio close to 1:1

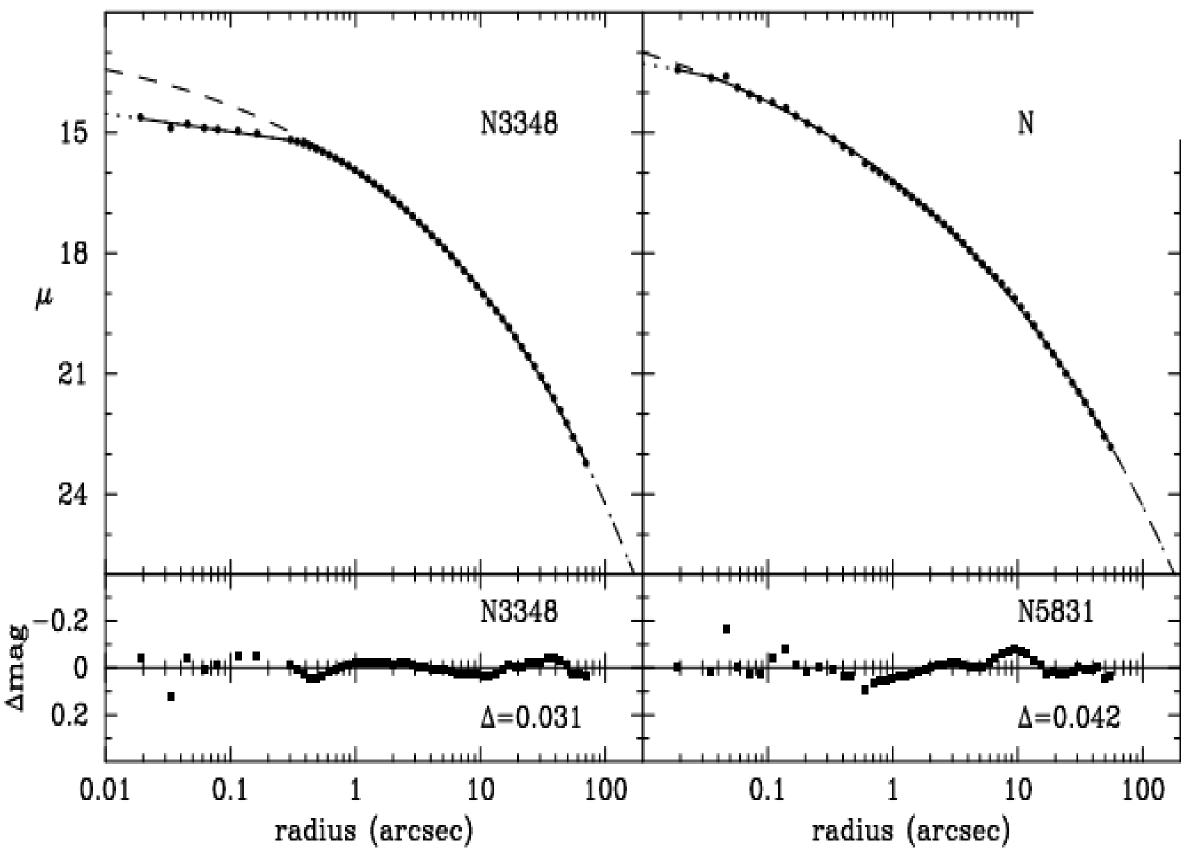
variation of profile shape (n) with L (Kormendy 2006)



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)

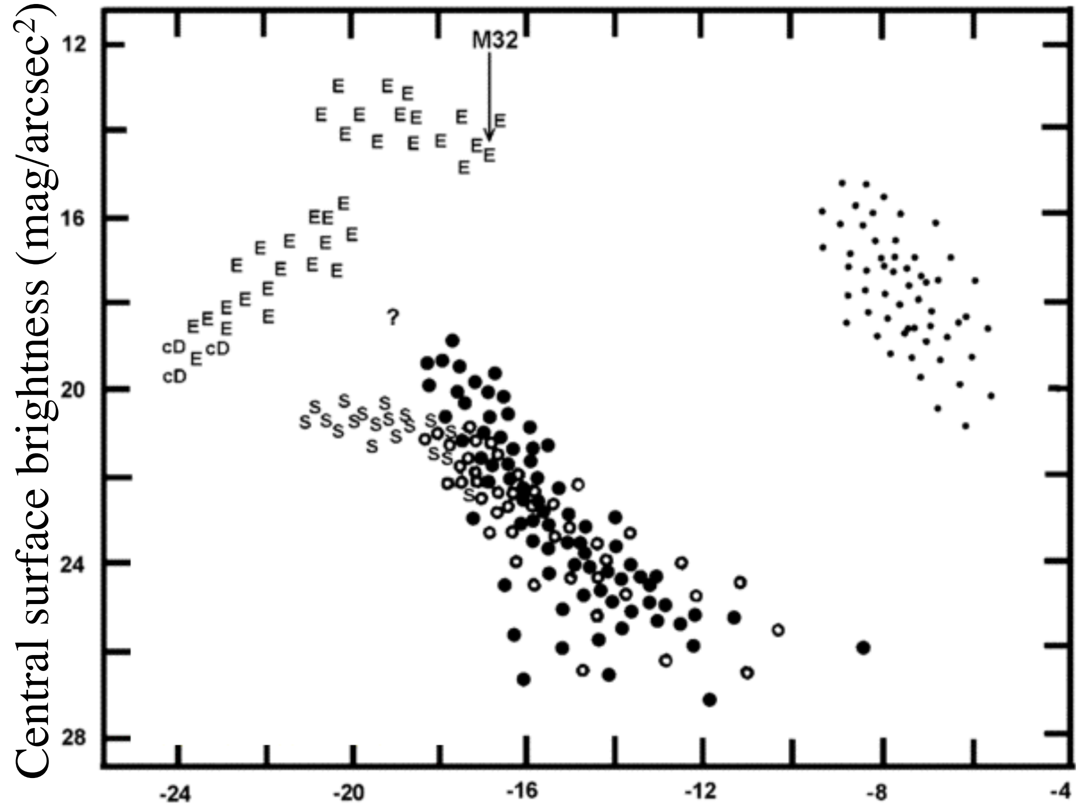




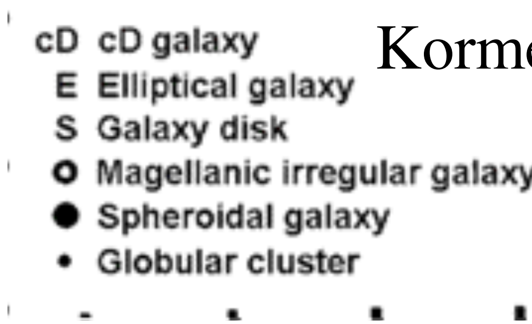
If n=4 (the deV model the total luminosity (S+G problem 6.1) is 7.22pR_e^2 I(R_e) and half the light comes from within R_e

Relevant Data

- Measure:
  - optical surface brightness distribution- well fit by Sersic law
- $\log I(R)=\log I(R_e)-b(R/R_e)^{1/n}-1$
  - b is chosen so that half of the light is inside R_e
  - Asymptotic limits :n=1 exponential, n=4; the $R^{1/4}$ law of deVacouleurs
  - Integrate the Sersic law(problem 6.1) to get the total luminosity $=7.22\pi I(R_e)R^2_e$
  - At $r \ll R_e$ one get deviations from this law.



Absolute B mag



Kormendy et al (2009)

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) are less flattened (ellipticity <0.15) than smaller Es;

(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.

(10) anisotropic and moderately triaxial

Normal and dwarf true ellipticals (M_V >21.5)

(1) are coreless and have central extra light with respect to an inward extrapolation of the outer Sersic 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 (still old but) younger stars with only modest or no α element enhancement;

(8) rarely contain strong radio sources, and

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

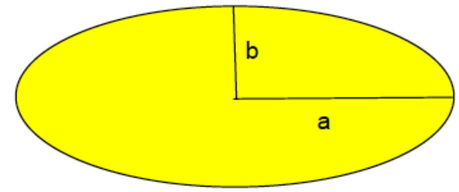
(10) nearly isotropic oblate spheroid

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

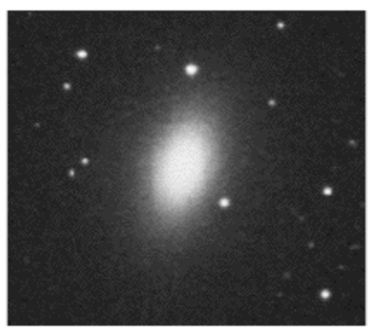
Apparent ellipticity
n=10(a-b)/a
=> En



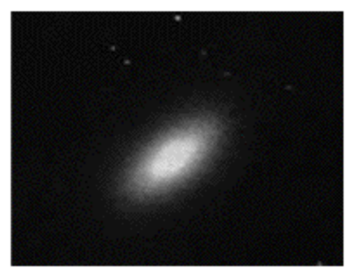
Observe E0 (round) to E7

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

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

- The radial deviations of the isophotes from the fitted ellipses can be expanded in a Fourier series of the form

$$\Delta r_i = \sum_{k=3}^{N} \left[a_k \cos(k\theta_i) + b_k \sin(k\theta_i) \right] .$$

- The most important parameter is a_4, if $a_4$4> 0,

the isophotes are disky;

If $a_4 < 0$, the isophotes are boxy.

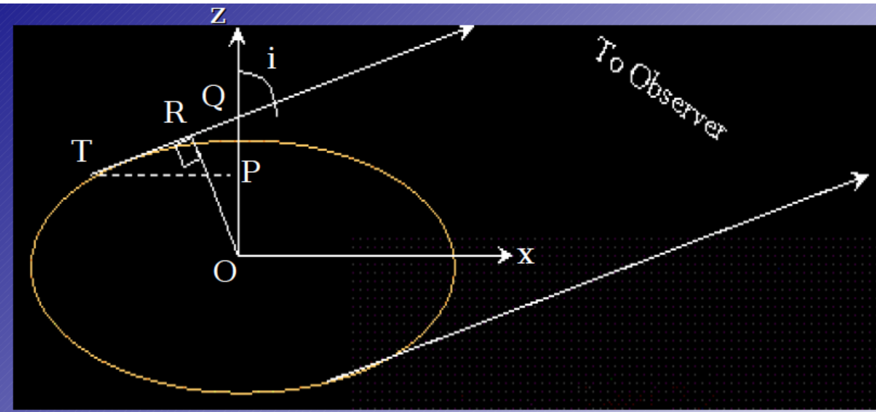
Ellipticals Shape

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

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

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 elliptical galaxies are oblate spheroids then

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

Distribution of B/A

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

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

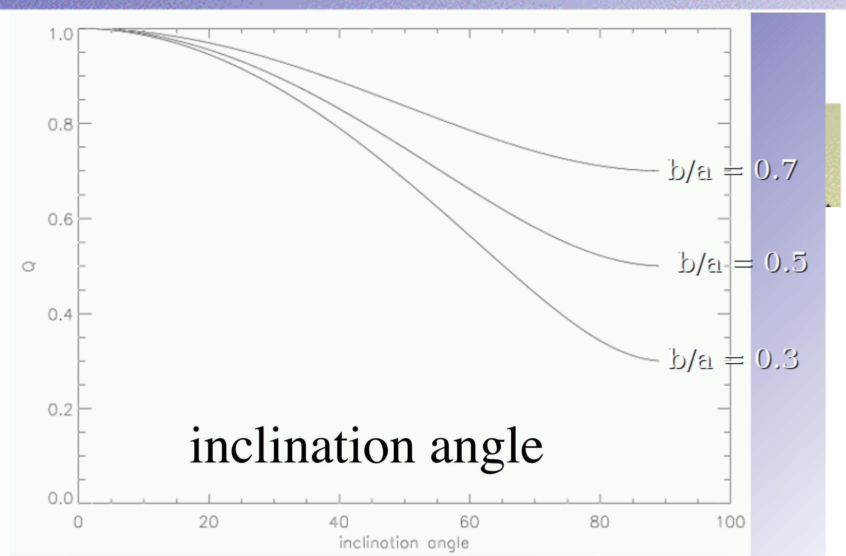
Using our definition of m for the last step. Finally we can rewrite this as

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

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

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

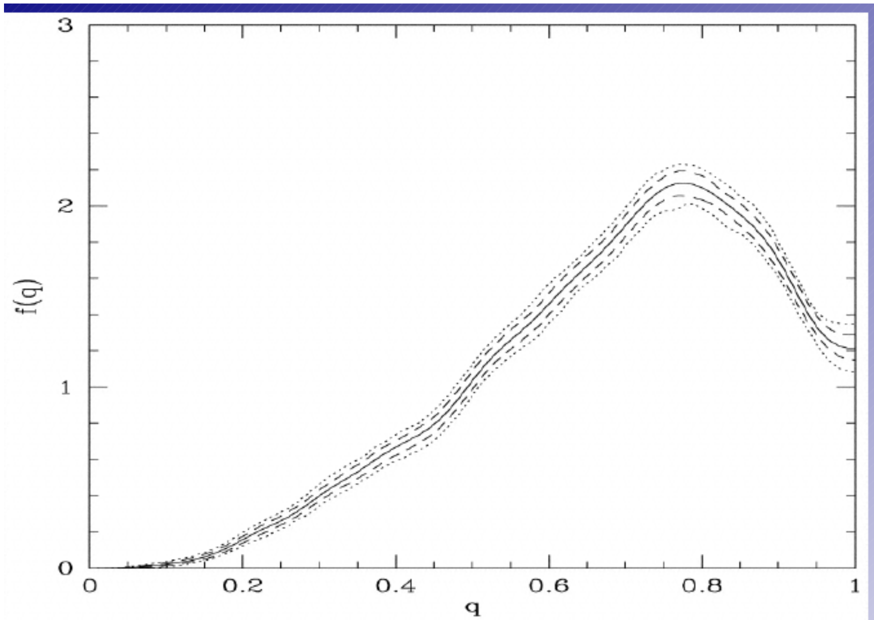
q



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.

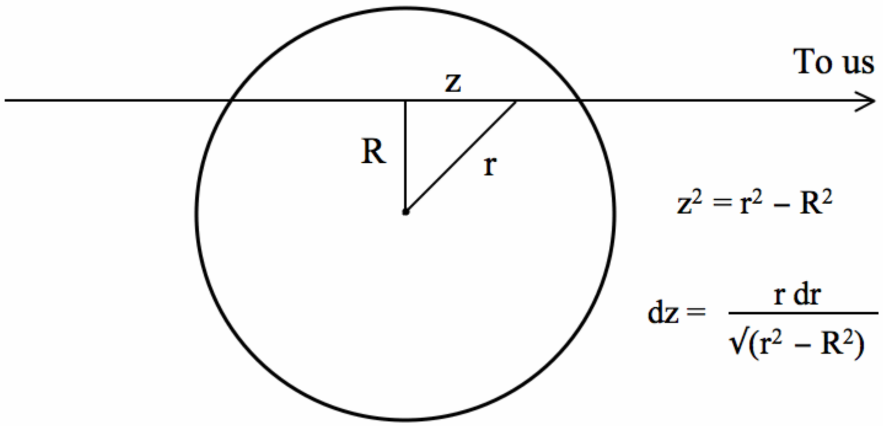


Axial ratios for galaxies fit with de Vaucouleurs profiles (Khairul Alam & Ryden 2002).

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)
- this is an Abel integral which has a few analytic solutions
- in general $j(r)=-1/\pi\int dI/dR \, dR/\text{sqrt}(R^2-r^2)$
- Try 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 and often a generalized King profile with surface brightness $I(r)=I(0)(1+(r/r_c)^2)^{-5/2}$ and density law $\rho(r)=\rho(0)(1+(r/r_c)^2)^{-3/2}$ where $r_c=3\sigma/\text{sqrt}(4\pi G p_c)$

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



$$z^2 = r^2 - R^2$$

$$dz = \frac{r\, dr}{\sqrt{(r^2 - R^2)}}$$

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 (not 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.

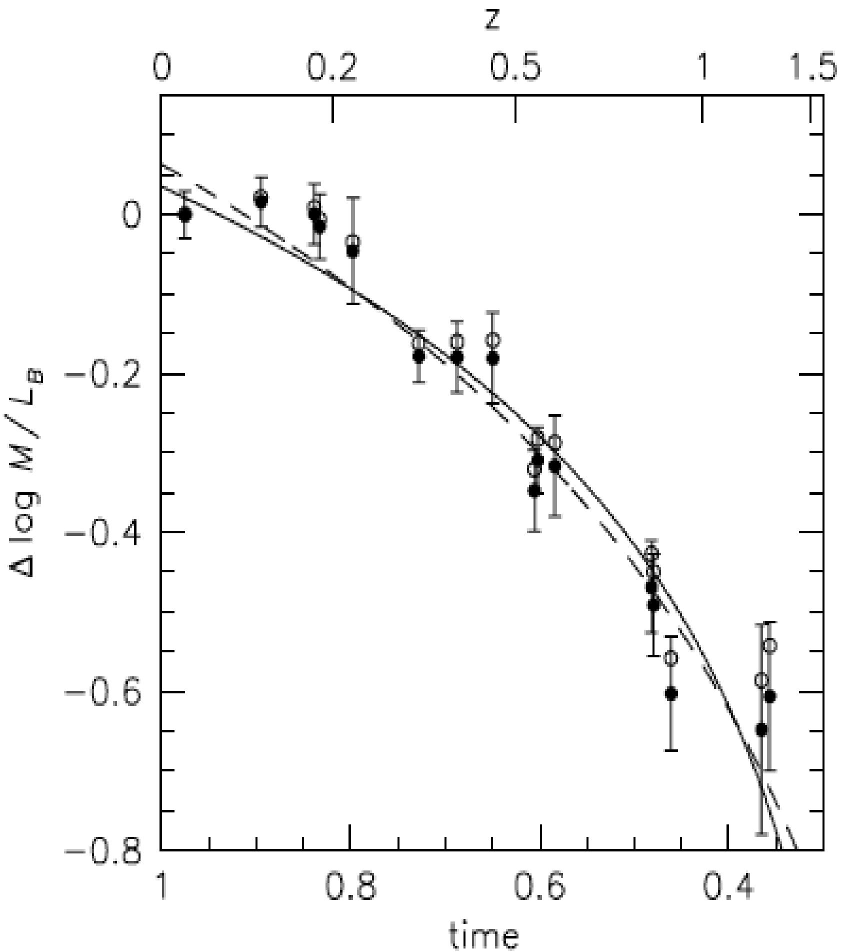
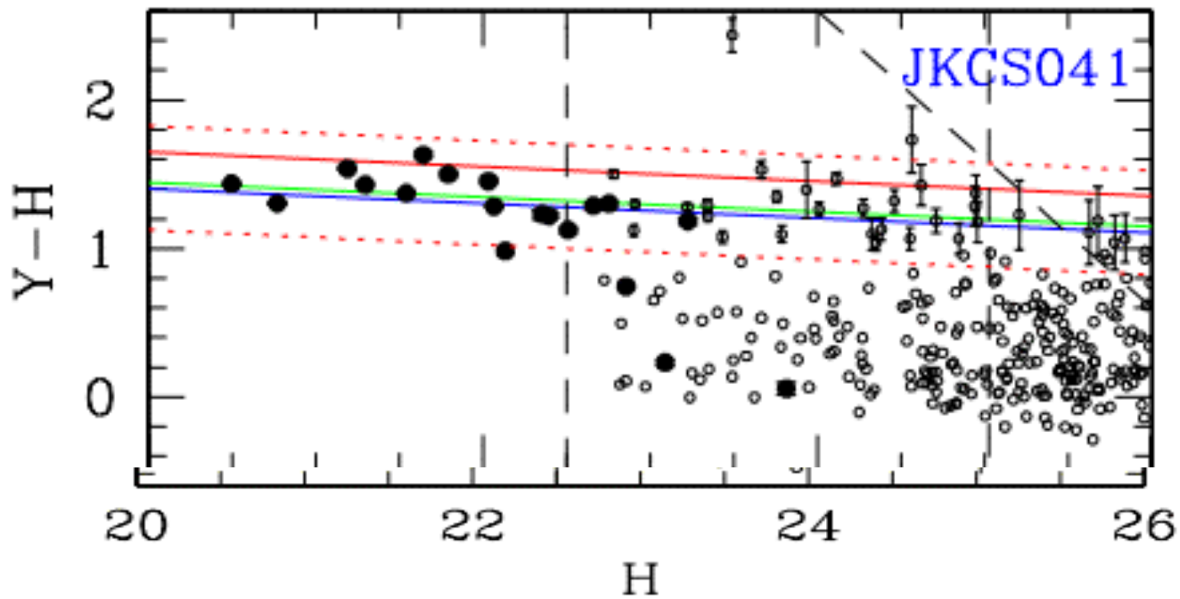


FIG. 8.— Evolution of the mean M/L_B ratio of massive cluster galaxies with time. Open symbols are the same datapoints as shown in Fig. 6. Solid symbols with errorbars are offset by $-0.05 \times z$ to account for progenitor bias (see text). The solid line shows the best fitting model for a Salpeter-like 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).

When Did the Galaxies Form

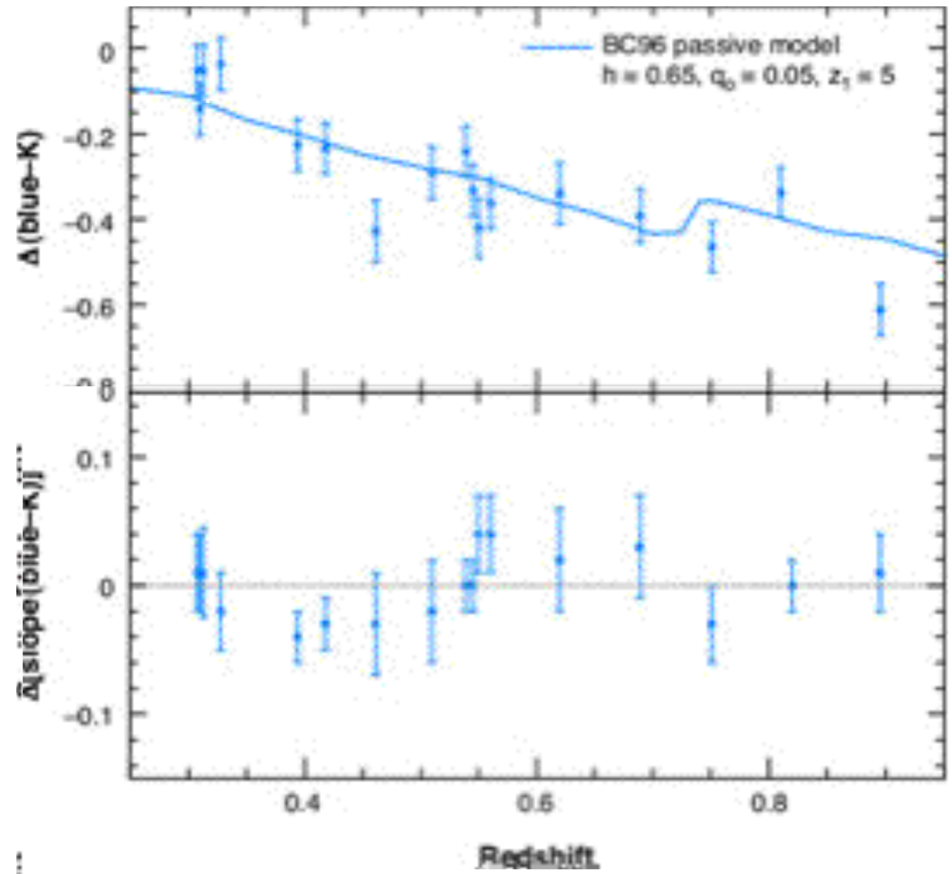
- Observations of high z clusters can break the degeneracy (Andreon et al 2013 (arxiv 1311.4363)
- Z=1.8 cluster; a spread in ages of only 380 Myr
- Remarkably the shape of the galaxy mass function of red sequence galaxies is unaltered over the last 10 Gyr

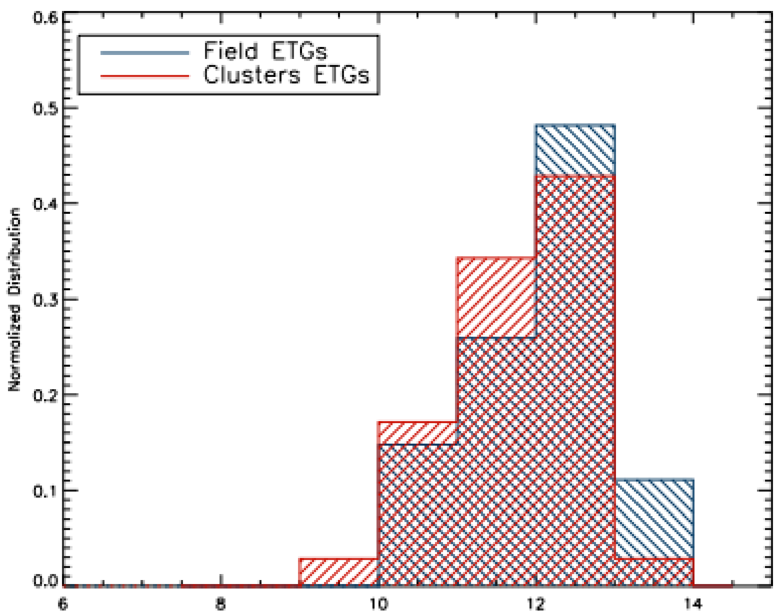


lines locus of a SSP with z_f = 5,3,2.5

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 (!)





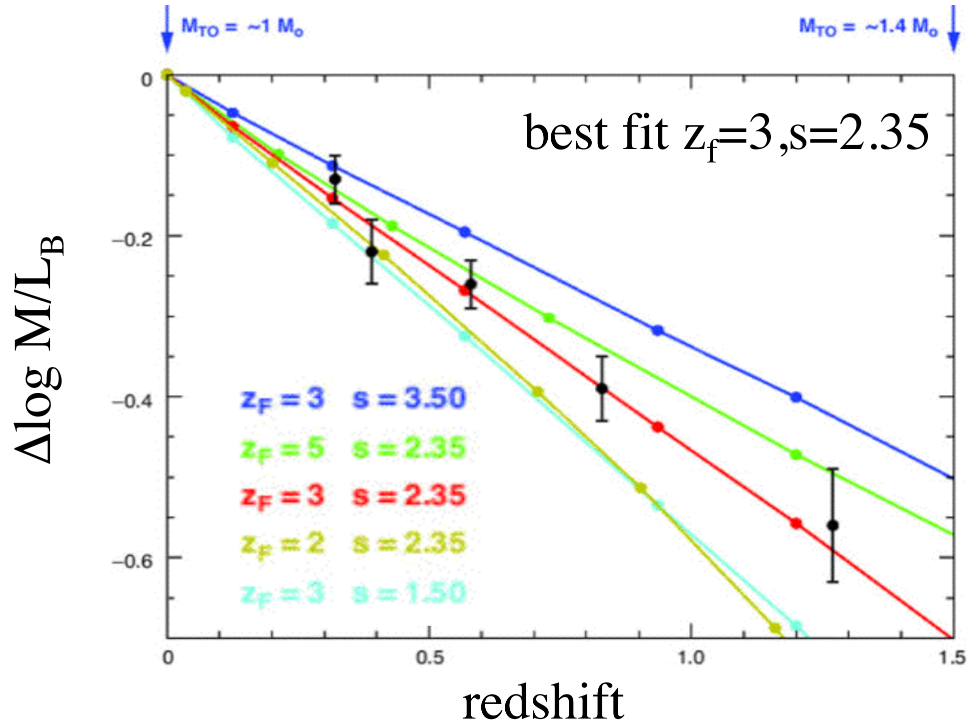
6 8 10 12 14

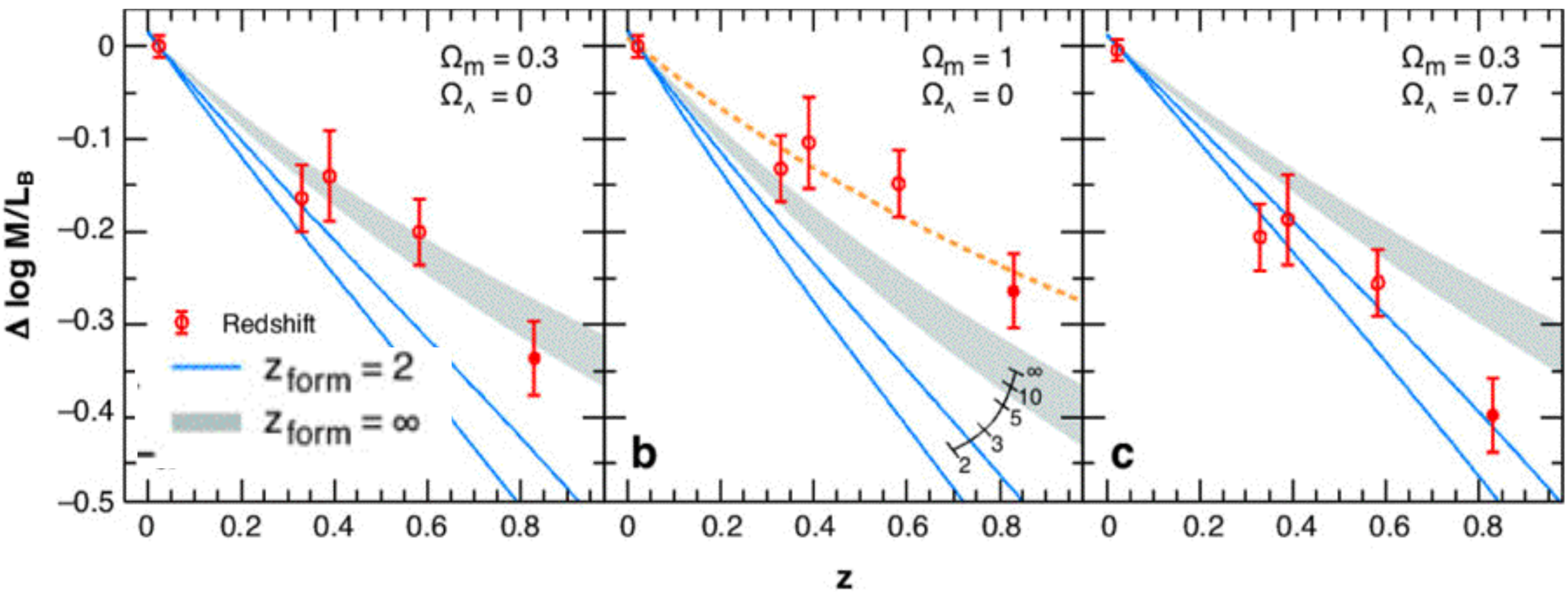
look back time of star formation (gyrs)

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

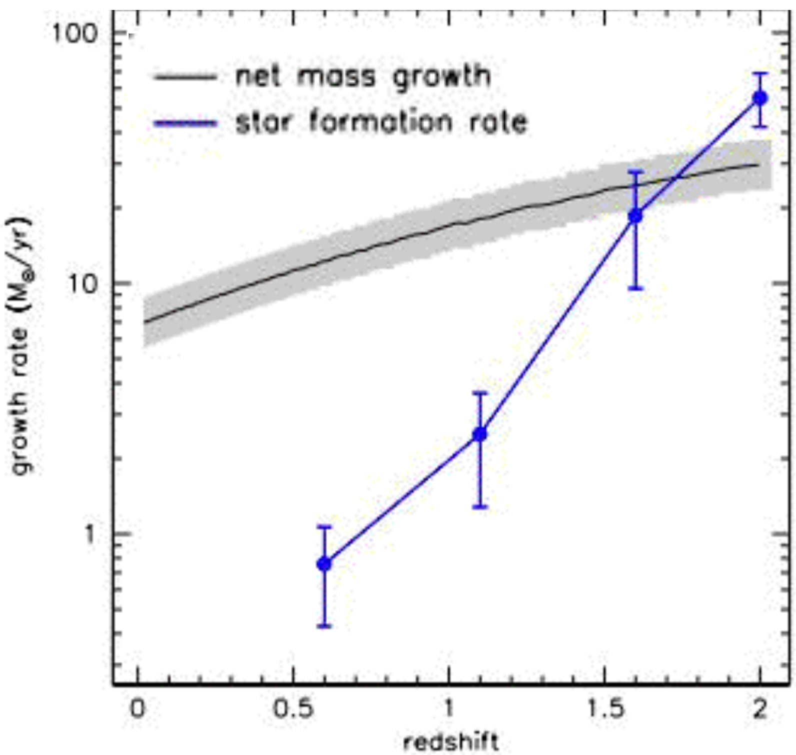
- 'age date' the galaxies with higher redshift observations
- The evolution with redshift of the M_* / L_B ratio of simple stellar populations of solar metallicity and various initial mass function slopes and formation redshifts:

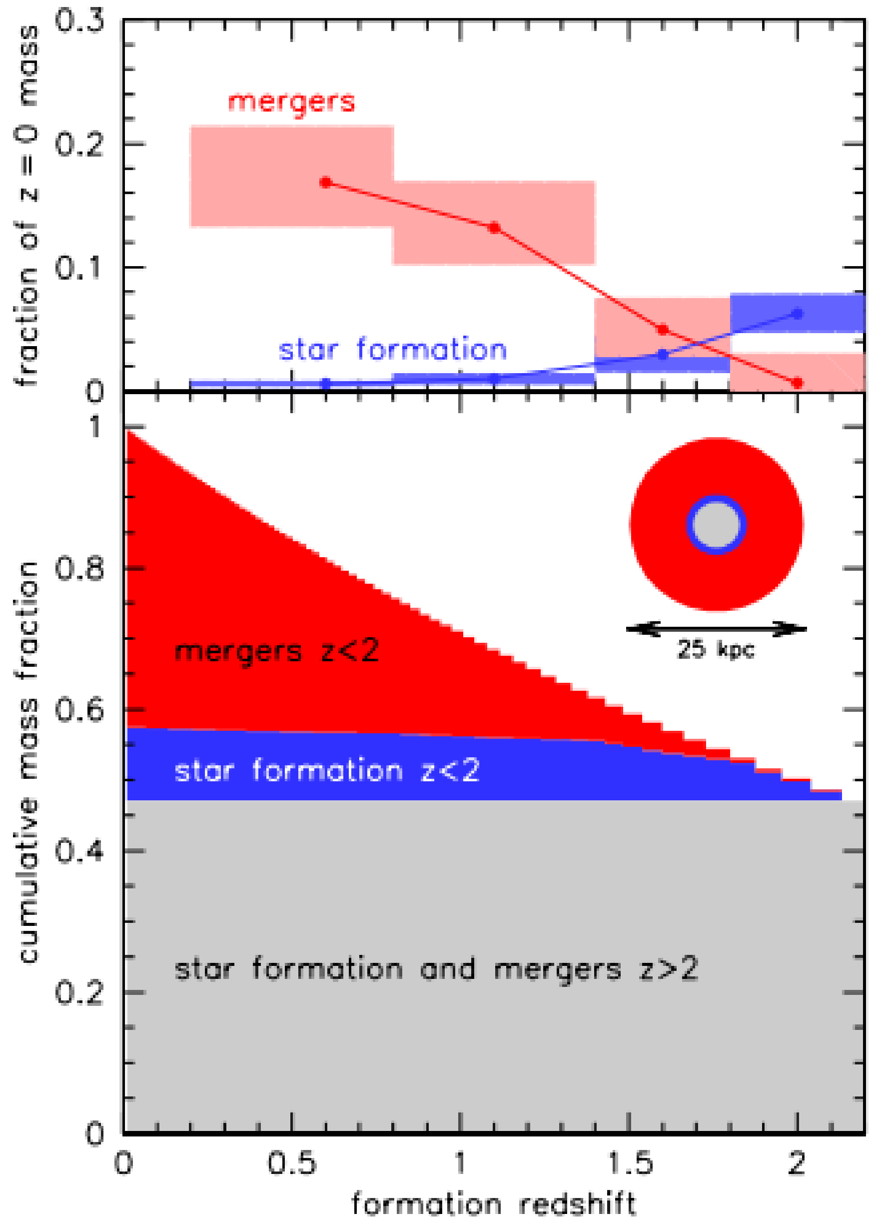




Growth of Elliptical Galaxies

- 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)

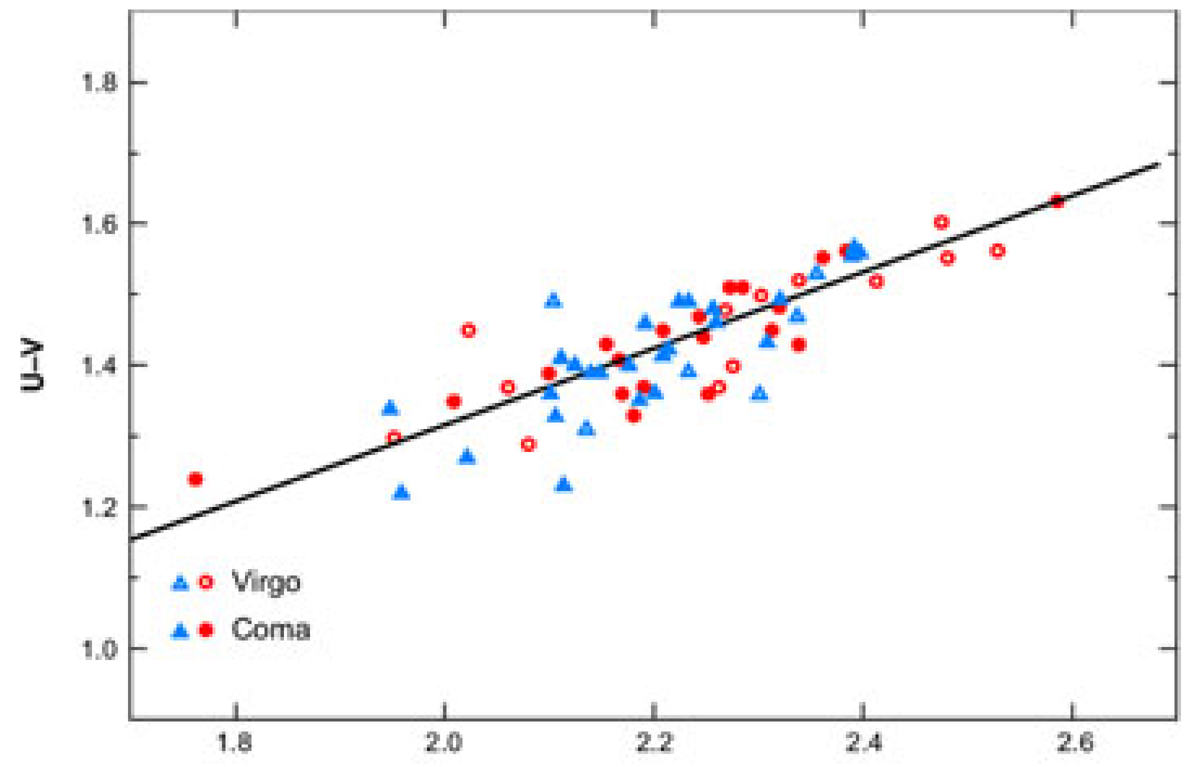




van Dokkum et al 2010

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,



log σ

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

Weds Dec 18 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 10

- That's NEXT week !!!
- WE CAN DISCUSS THIS??

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.

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

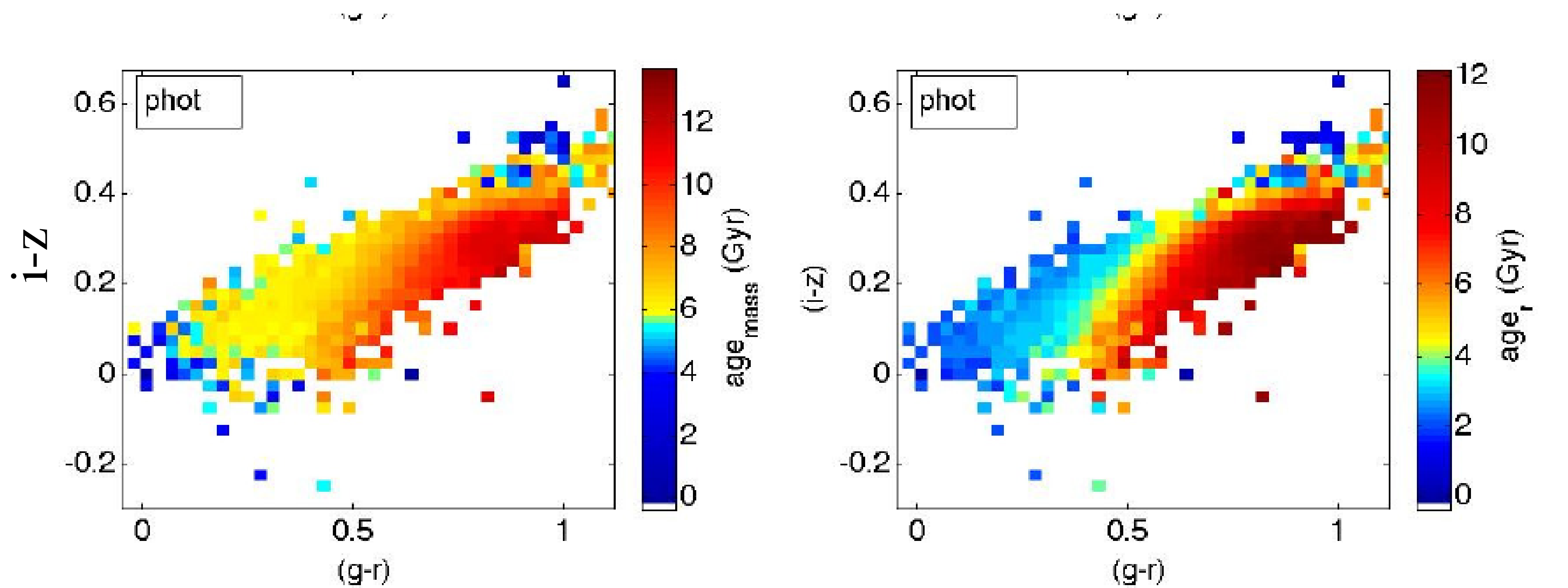
isotropic oblate flattened spheroids

'coreless'- power law inner slopes

smaller Sersic indices

Colors

- Its much easier to obtain broad band colors of galaxies than spectra
- Via use of spectral evolution codes and cross checks with higher resolution spectra one can obtain reasonably reliable information on metallicity, ages and star formation rates from colors
- The optical colors of elliptical galaxies are sensitive to a combination of age, metallicity and α-enhancement, while the optical-infrared colors are sensitive to metallicity and to α -enhancement, but are somewhat less sensitive to age.



left panel is the mass weighted age distribution- right panel the age distribution weighted by r band flux

Optical Spectra

- The spectra of elliptical galaxies are dominated by emission from K giant stars, but comprising some mixture of stellar types depending on the age, metallicity, and metal abundances of the stellar population- connection of galaxy dynamical, imaging and stellar properties.
- thus ellipticals all have nearly the same optical broad-band color, with a weak dependence of color on galaxy luminosity (stellar mass or velocity dispersion).
- This dependence is due to both age and metallicity trends as a function of mass
- Little dust, so reddening is a minor issue

Spectra

- With sufficient cleverness one can stack the spectra obtained from the SDSS based on photometric data (Conroy et al arxiv 1303.6629) - this is a very nice summary and I recommend that you read it.

2 CONROY, GRAVES & VAN DOKKUM

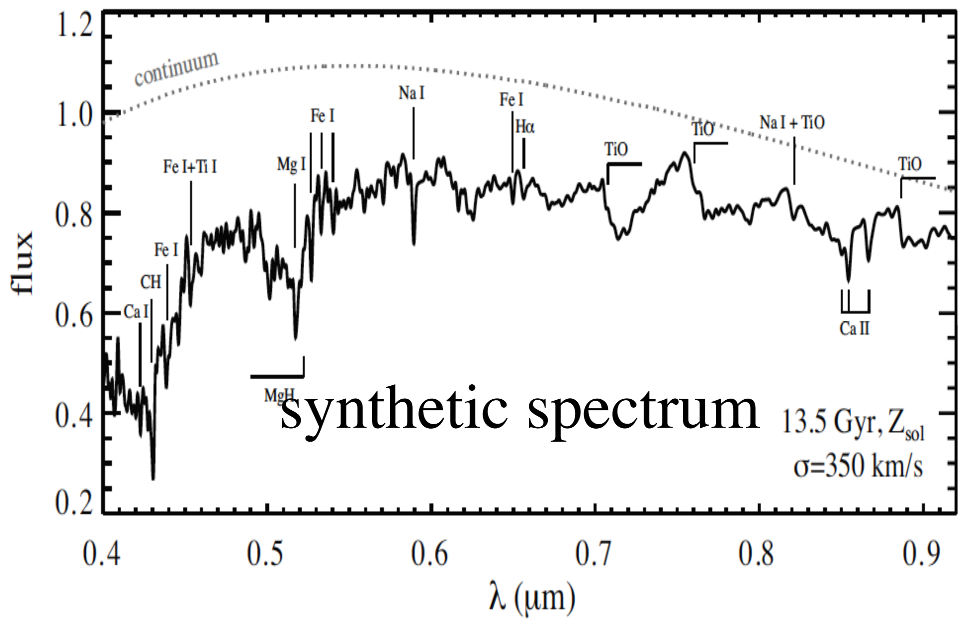


Figure 1. Model spectrum for an age of 13 Gyr and solar metallicity. The spectrum has been smoothed with a velocity dispersion of $\sigma = 350$ km s^{-1}, equal to the smoothing applied to the early-type galaxy data analyzed in this paper. Strong features are labeled. Also included is the location of the true stellar continuum, which is the spectrum that would be observed in the absence of all line opacity. In this figure the model spectrum is computed entirely from synthetic stellar spectra, whereas for the main analysis the synthetic spectra are only used differentially.

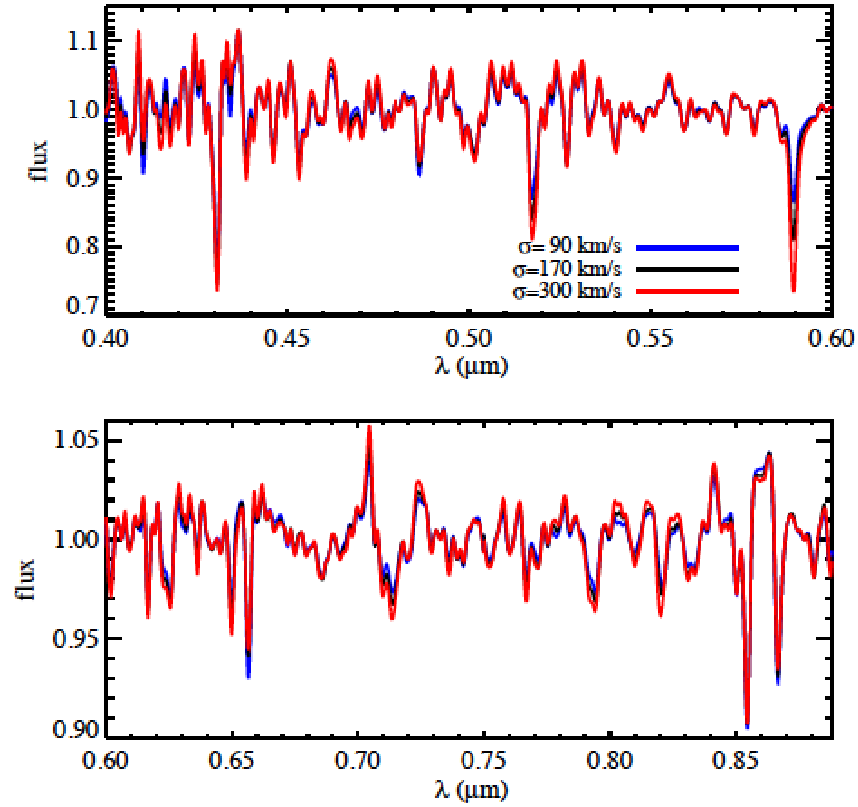
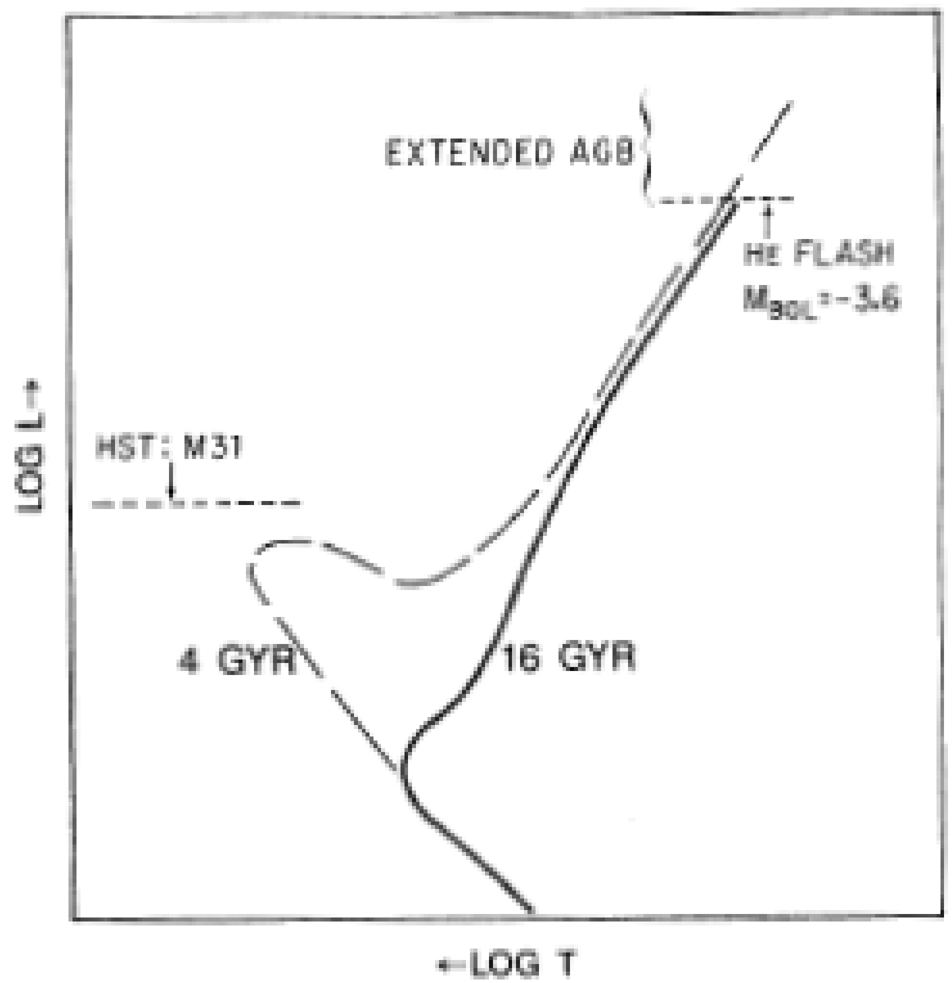


Figure 7. Continuum-normalized stacked spectra of SDSS early-type galaxies in three velocity dispersion bins.

stacked data in 3 velocity dispersion bins

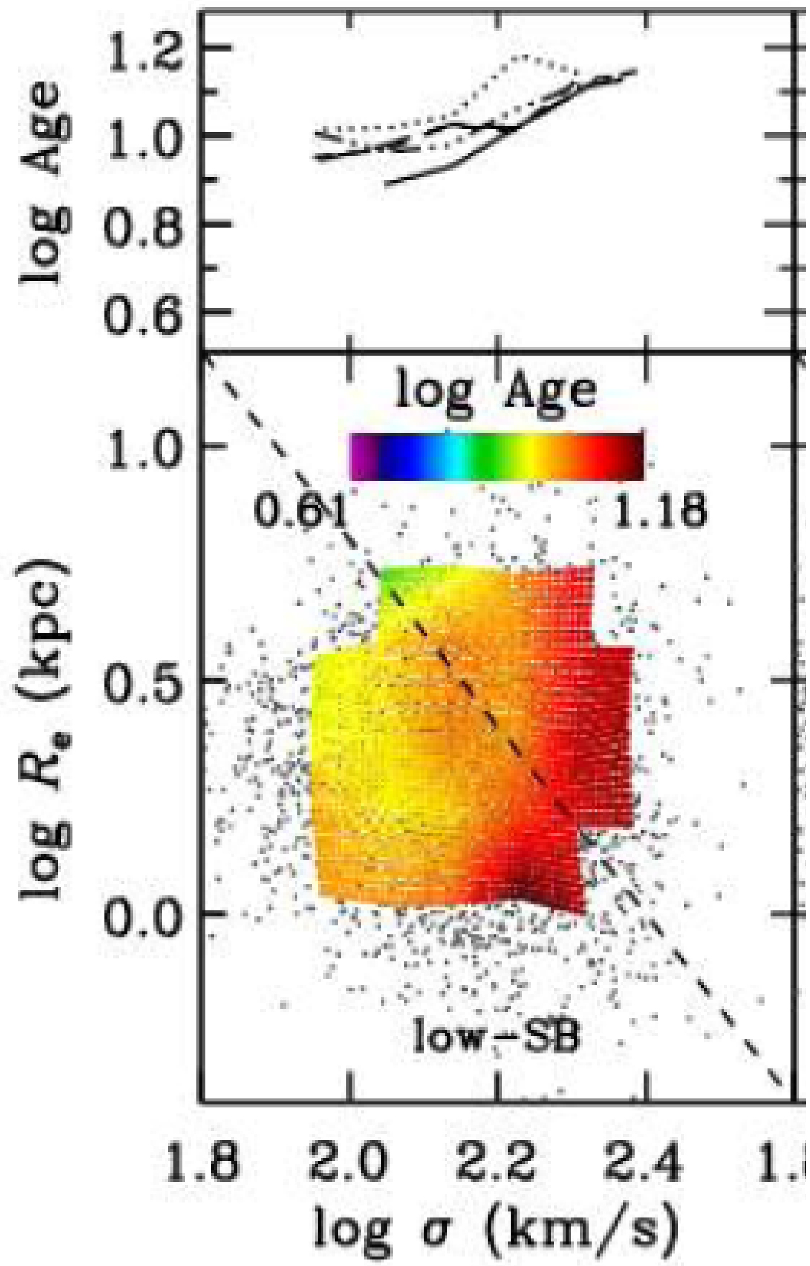
Problem in Getting Ages

- The problem is that most of the stellar light is from giants but most of the mass is on the Main Sequence
- On the giant branch there is not much difference between 4 and 16Gyr aged populations



Relationship Between Surface Brightness, Size,Velocity and Age of Stars -*chemical composition of the stars in the galaxies knows about the large scale properties of the galaxies*

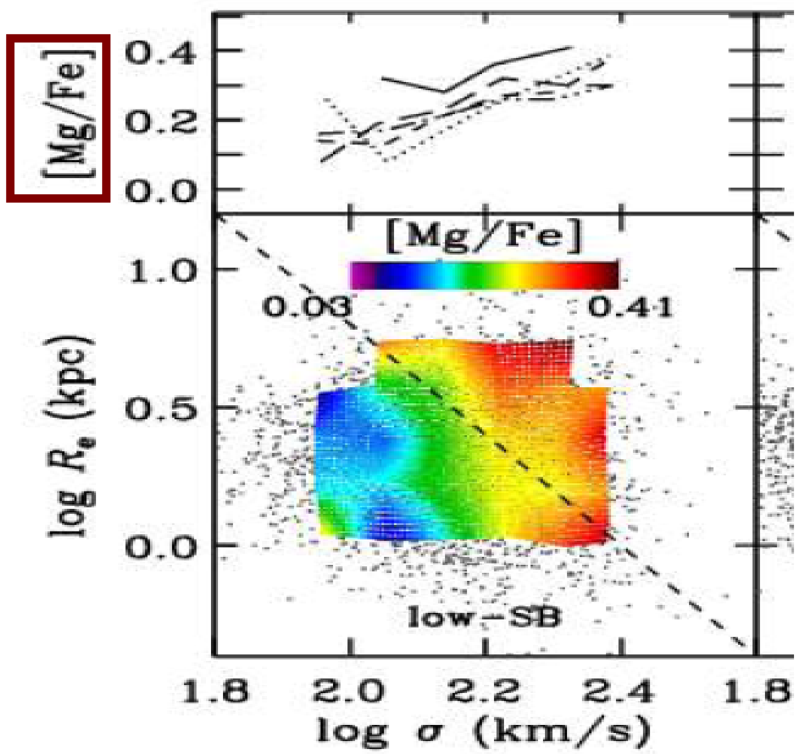
Strong connection of chemical composition structural parameters, mass, age...
Strong clues to how stars/galaxy form...



- lines of constant age run nearly vertically, indic population age is independent of R_e (scale lengt σ (stellar velocity dispersion.

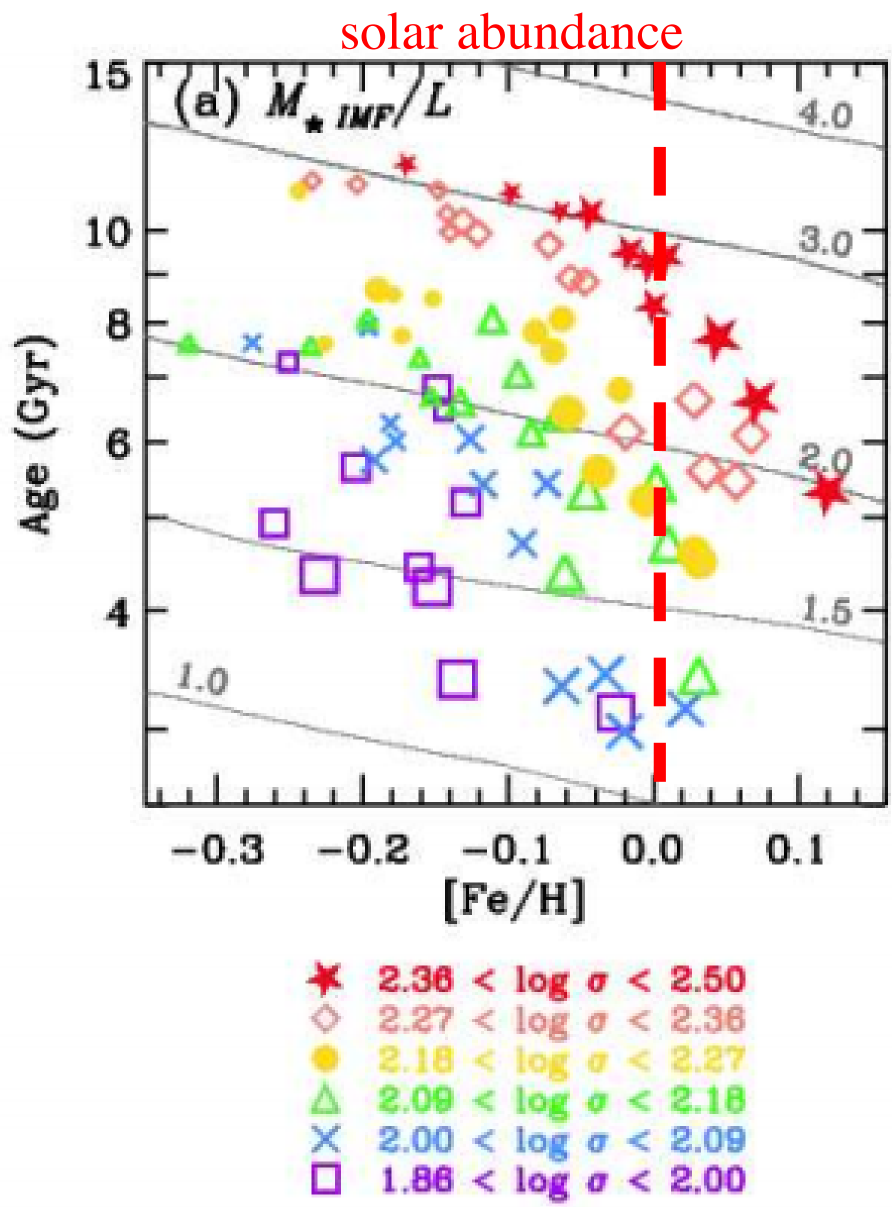
Metallicity

- Stellar halos of massive ellipticals have high metallicities and high [α/Fe] ratios -
- very old stars **but as opposed** to MW halo high metallicities
- More massive (higher σ) systems- older, more metal rich higher [α/Fe]
- galaxy formation occurred before a substantial number of Type Ia SNe could explode and contribute much Fe?



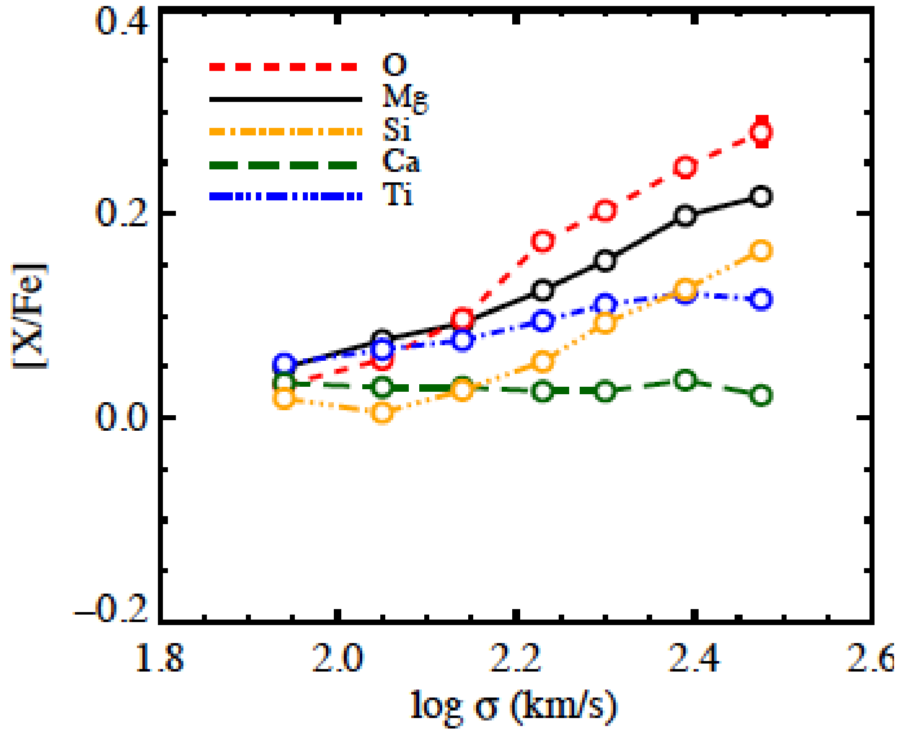
Gray-lines of constant M/L

Graves et al 2010

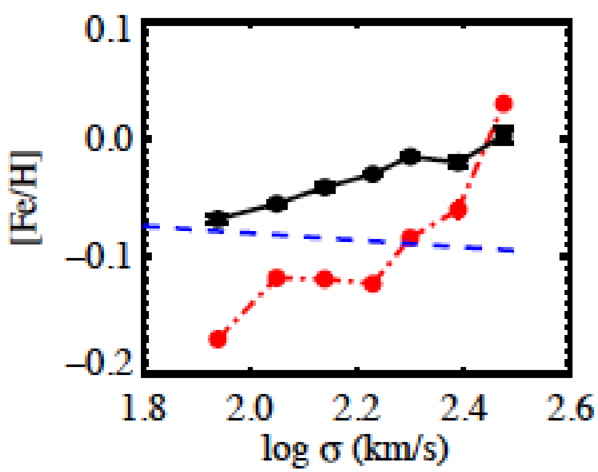


Metallicity

- Early-type galaxies are enhanced in the α element Mg compared to the abundance patterns of stars in the Galactic disk (Worthey 1994).
- The [α/Fe] ratio is sensitive to
  - the timescale of star formation,
  - the slope of the initial mass function (IMF) at > $1M_{\odot}$,
  - the delay time distribution of Type Ia supernovae (SNe)
  - the preferential loss of metals via winds

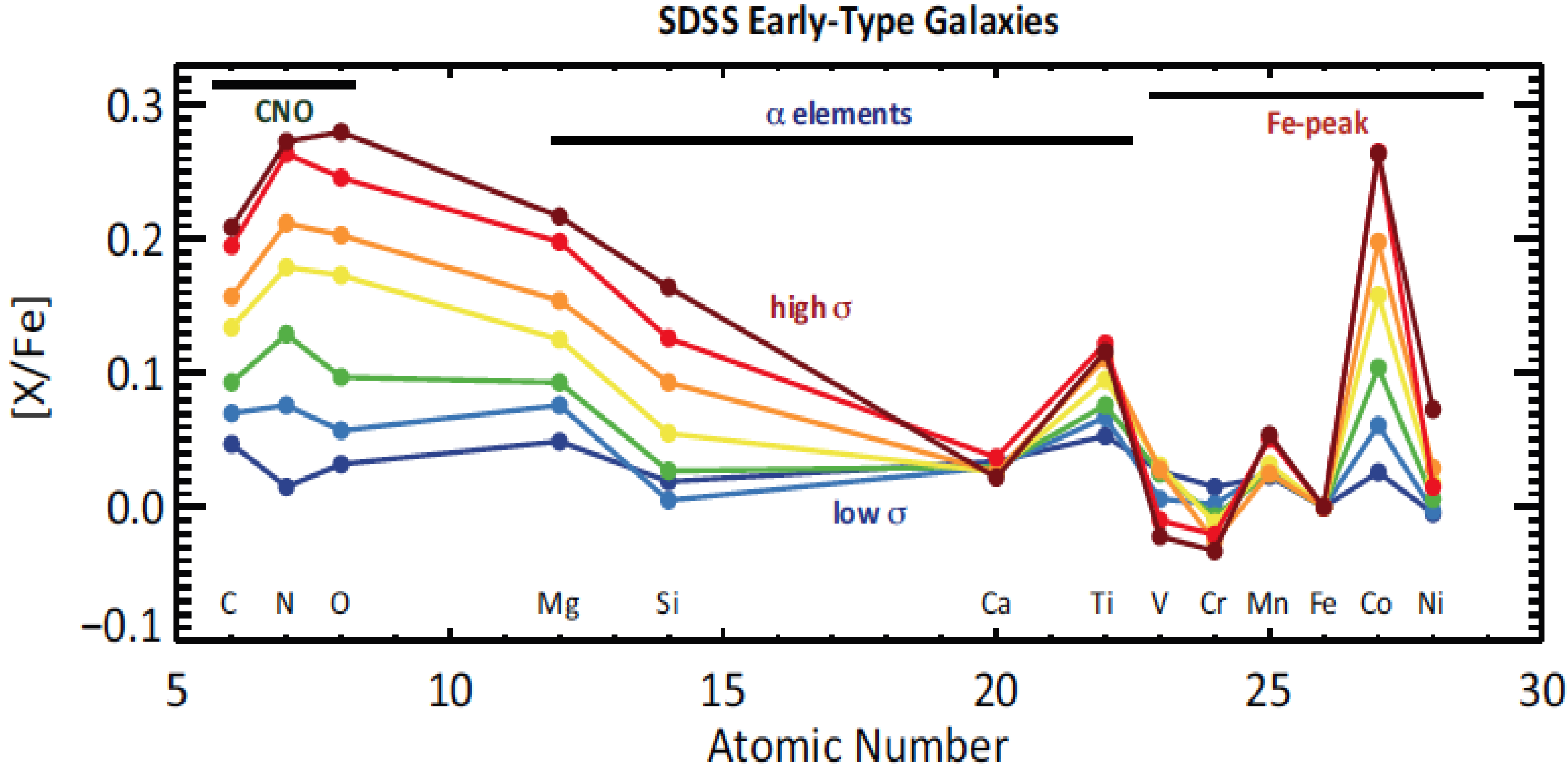


Conroy et al 2013



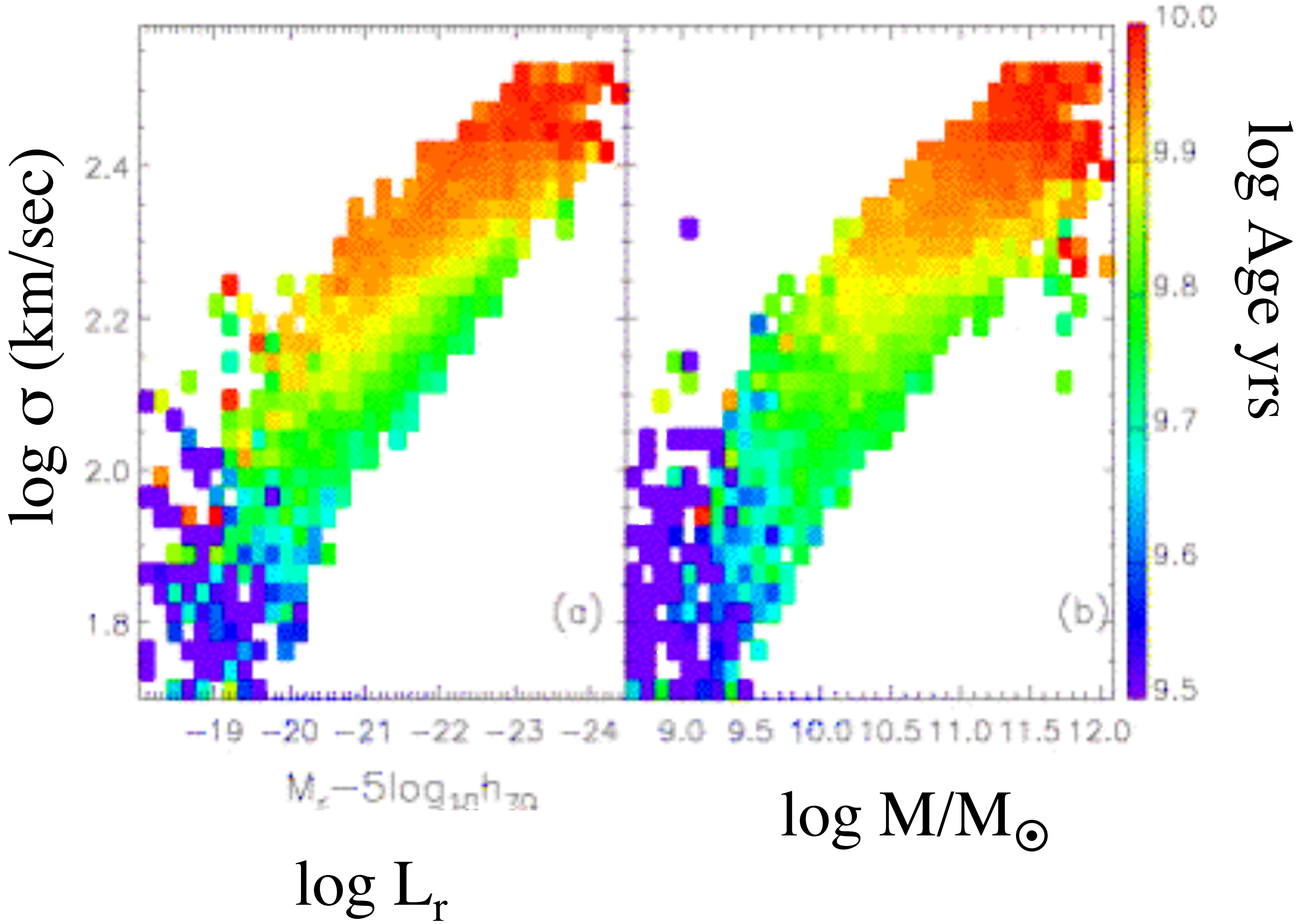
still fundamental uncertain
due to technique

Patterns from Spectroscopy



Conroy et al 2013

More Massive Galaxies are Older



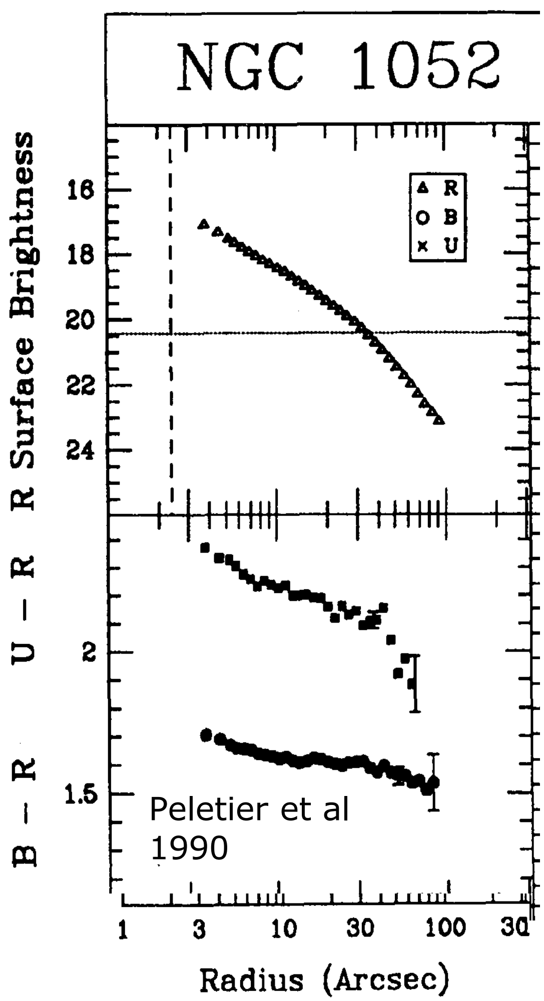
- small but systematic trends for more massive and luminous galaxies tend to be older

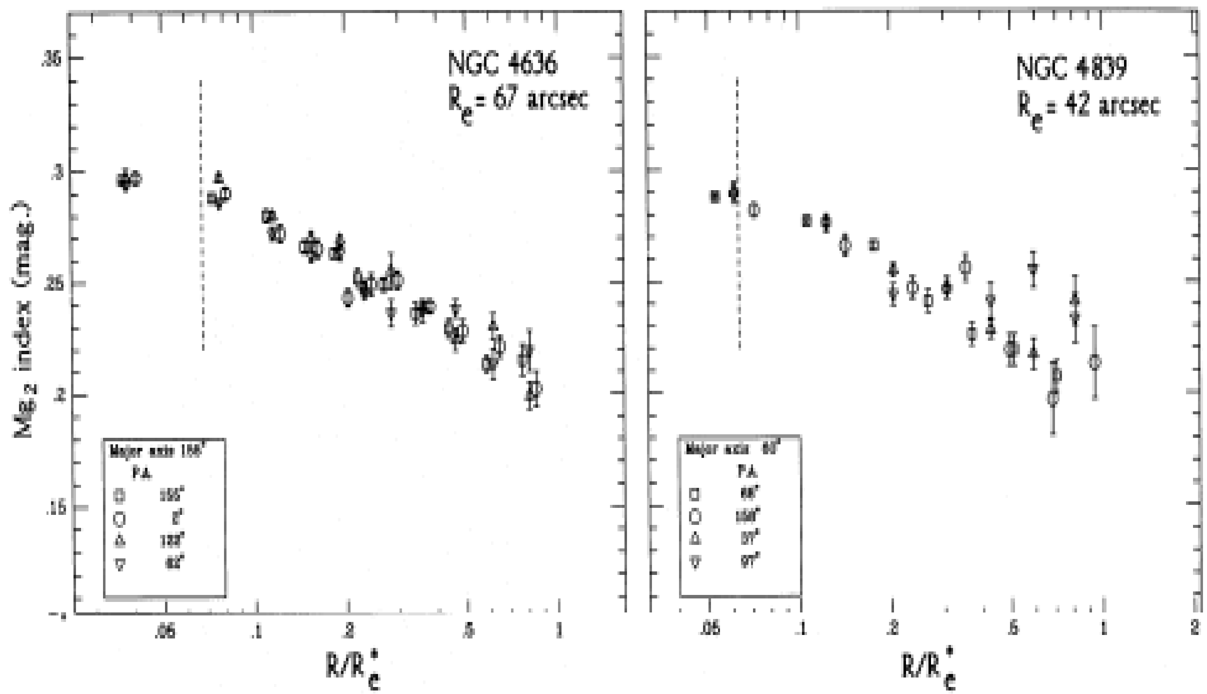
Global Properties

- E galaxies become redder toward their centers. These gradients are fairly subtle; a factor of 10 decrease in radius typically produces a change of ~ 0.25mag in(U-R) and ~0:1mag in(B-R) (Franx, Illingworth, & Heckman 1989b)
- This could be due to either a metallicity or age gradient
- Detailed analysis (Graves et al 2010) shows that it is **primarily a metallicity gradient** (center is more metal rich on average) - a factor of 2 over a range of 10 in radius- but at any given radius there is a range in metallicity

Color Profile

- Almost all galaxies become bluer outward- mostly due to decreasing metallicity

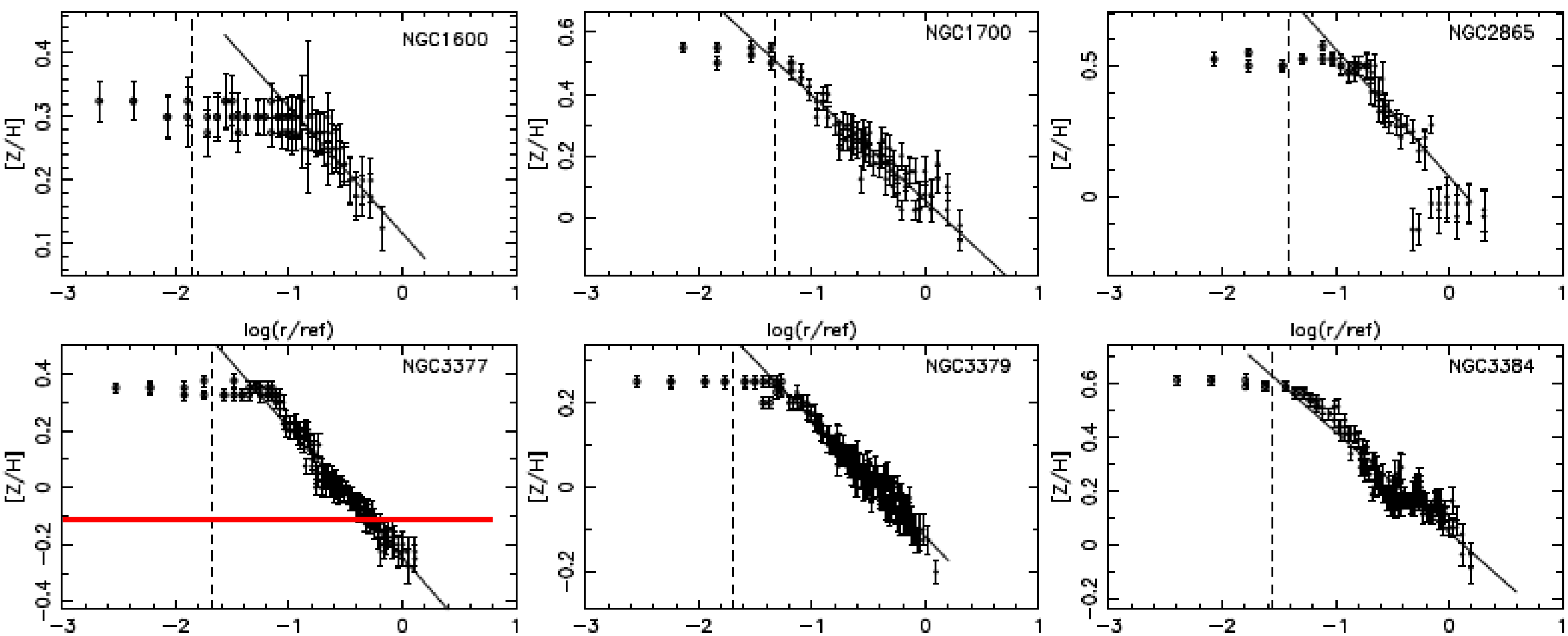




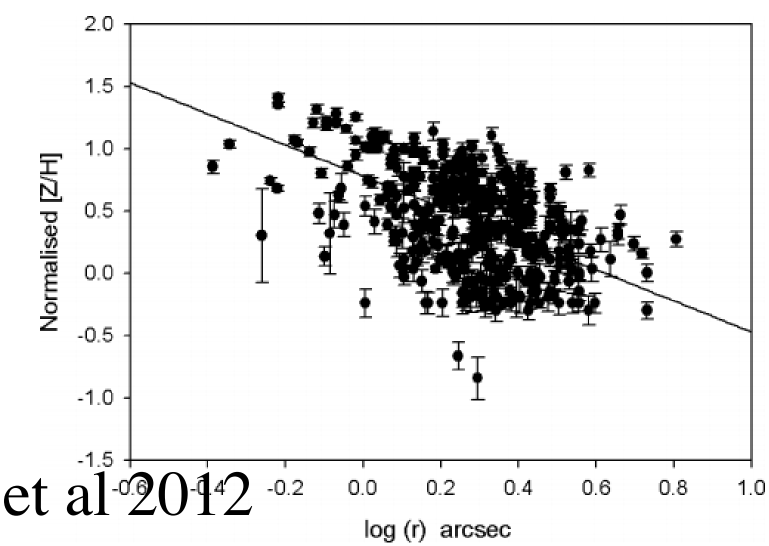
Because of the color-age degeneracy its not clear what causes the color gradients without spectra

Stellar Abundance gradients

P. Sánchez–Blázquez et al.



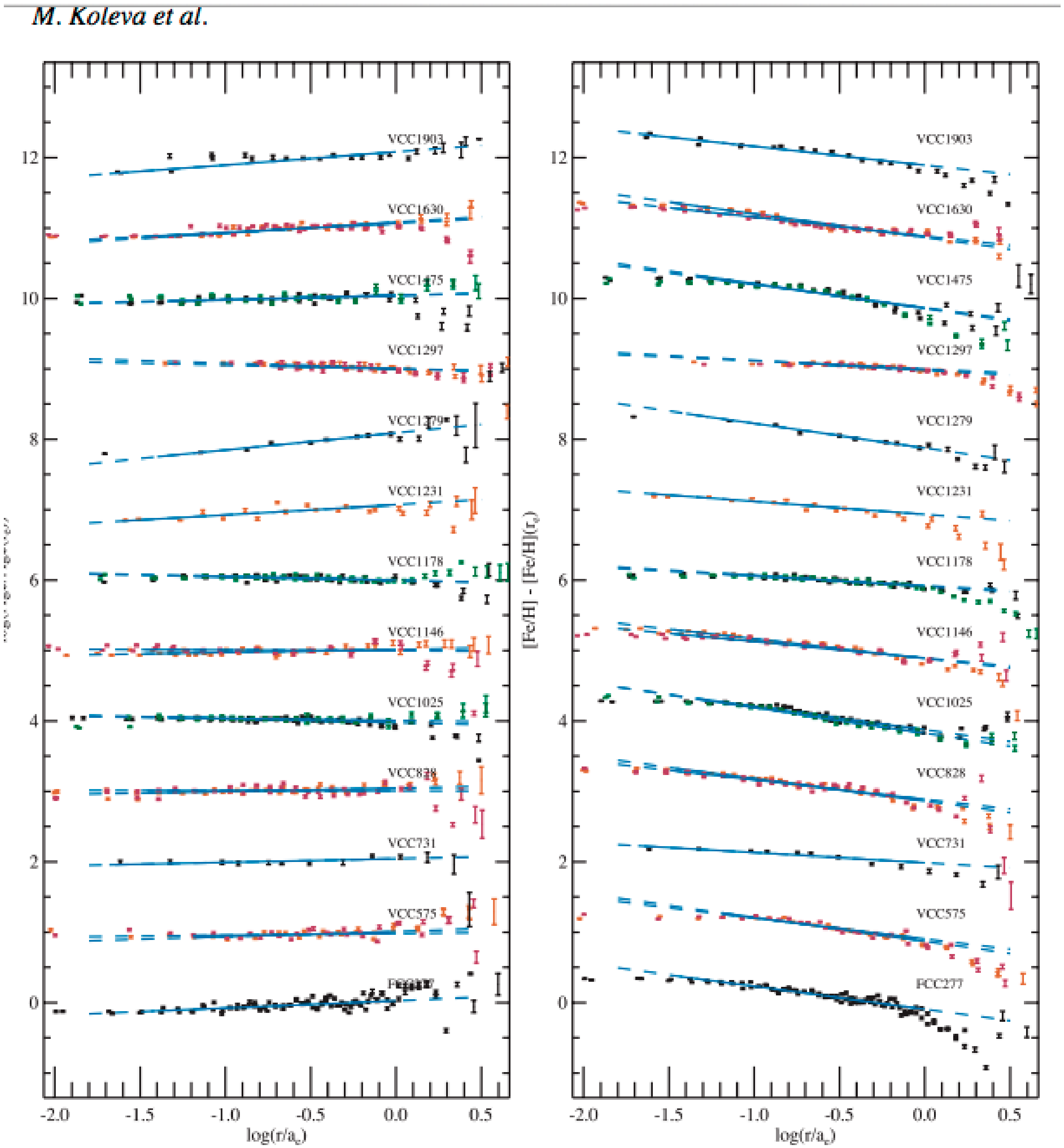
- stellar abundance drops with radius~ factor of 2, dZ/logr~-0.3 but optical data only extend to ~R_{e-} xrays go further out
- Super solar values in centers
- Weak age gradient



Loubser et al 2012

Abundance Gradients

- There is a well known abundance gradient in the outer regions of elliptical galaxies (Greene et al 2013, Koleva et al 2011)



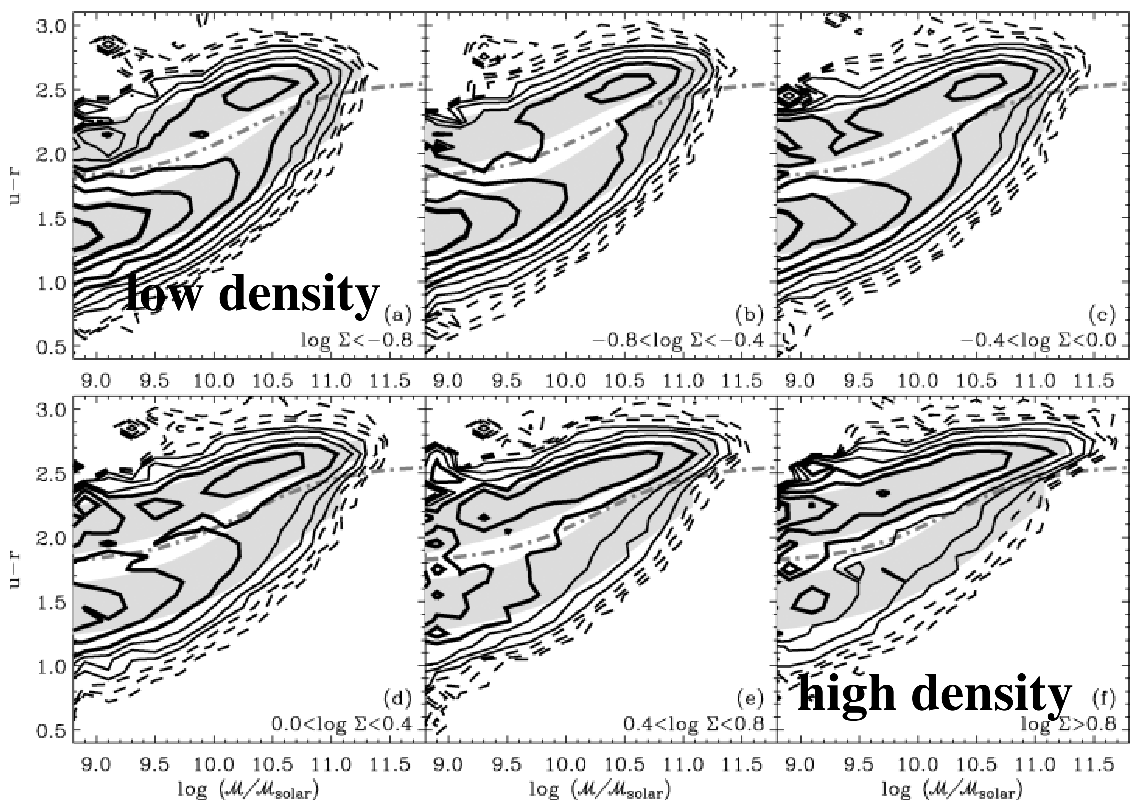
Summary of Abundance Data

- All early-type galaxies obey a metallicity–luminosity relation
  - less massive galaxies contain less metals
- outer regions have lower abundances but similar abundance ratios
  - weak age gradients
- All massive early-type galaxies have an age–luminosity relation
  - less massive galaxies have younger stellar populations, in an SSP sense.
  - This is the well-known downsizing effect; the least massive galaxies continue to form stars until present, while the most massive galaxies stopped forming stars at an early epoch

Environment

Baldry et al 2006

- Elliptical galaxies tend to occur more frequently in denser environments (morphology-density relation (Dressler 1980)
- As the environment gets denser the mean mass of the galaxies rises and their colors get redder- relative importance of the red sequence (ellipticals rises) -Both stellar mass and environment affect the probability of a galaxy being in the red sequence.



each panel shows the color mass plane with isophotes as the **local density rises** the relative number of galaxies in the red vs blue sequence increases

each box is an increase by 2.5 in density

Why Should Ellipticals Be In Denser Environments

- Formed that way
- Made that way

- Formed that way: Cold dark matter hierarchical models predict that denser regions collapse first (e.g are older today)
  - we know that that the stars in ellipticals are older so it makes sense for ellipticals to preferentially be in denser regions. But WHY ellipticals??
- Made that way

  in the densest place in the universe, rich clusters of galaxies physical processes occur (e.g. ram pressure stripping, galaxy harassment) that tend to destroy spirals. - BUT if ellipticals are primarily formed by mergers, this cannot happen in massive clusters since the galaxies are moving too fast to merge (e.g if relative velocity is greater than the internal velocity dispersion do not merge, but can harass).

Luminosity Functions

- Schechter function

$\Phi(L)=\Phi^* L^{\alpha} Exp(-L/L^*)dL$

Φ^* is a normalization constant

L^* is a 'characteristic' luminosity

α is the low luminosity slope

Integrate over L and total luminosity $J=\Phi^* L^* \Gamma(\alpha+2)$ where Γ is the gamma function

$\Phi^* \sim 4.5\text{x}10^{-3}$ Mpc^3

$L^*=2\text{x}10^{10}L_\odot$

Roughly $\alpha\sim-1.2$; $J=10^8 L_\odot/Mpc^3$

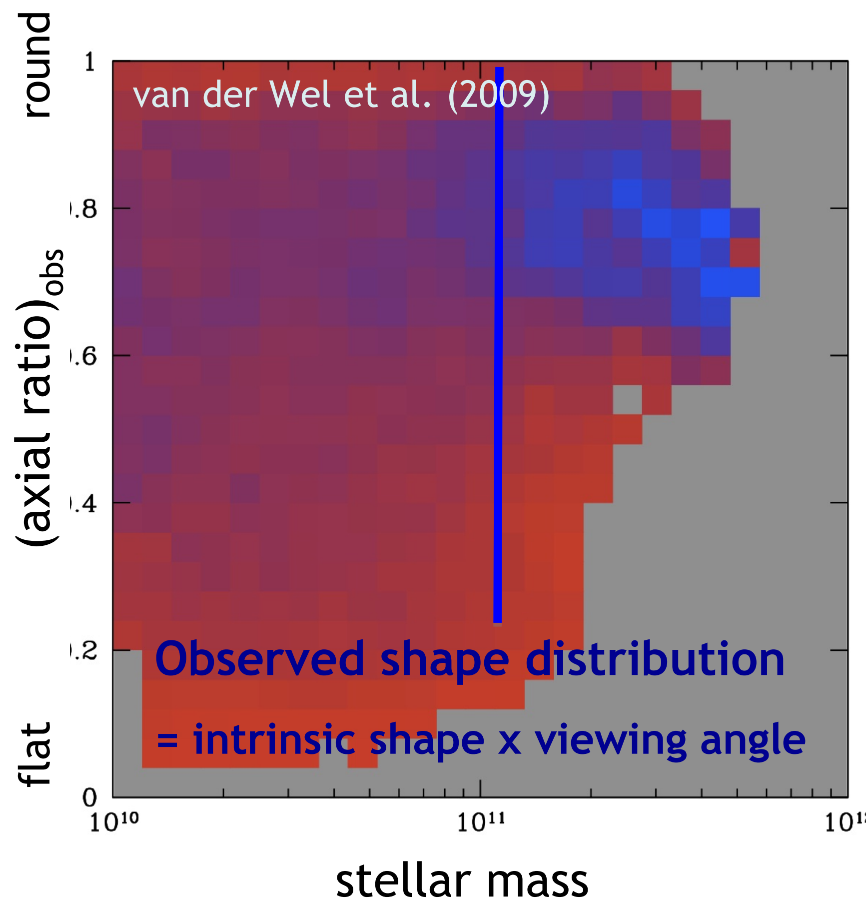
(Being perverse astronomers still frequently use magnitudes and thus one has M* (which depends on color) $M^*_B\sim-21$

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



Faber-Jackson

- Roughly, L ~ σ^4
- – More luminous galaxies have deeper potentials
- follows from the Virial Theorem
- Recent scaling relations (Cappellari et al 2006) find $M=5R_e\sigma^2_e/G$

6 observables are all correlated via **the fundamental plane**
Luminosity, Effective radius,Mean surface brightness,
Velocity dispersion, metallicity, dominance of dispersion over rotation

The F-P due principally to virial equilibrium
To first order, the M/L ratios and dynamical structures of ellipticals are very similar : thus the populations, ages & dark matter properties are similar
There is a weak trend for M/L to increase slightly with Mass
fundamental plane : measurements of σ and surface brightness profile correlated with (M/L)

Virial Theorm and FJ relation

- Potential of a set of point masses, total mass M, inside radius R is $U=-3/5(GM^2/R)$
- $KE=3/2M\sigma^2$
- use viral theorem $2KE+U=0$; $\sigma^2=(1/5)GM/R$
- if M/L is constant $R\sim LG/\sigma^2$
- $L=4\pi R^2 I$ (assume for the moment that surface brightness I is constant)
- $L\sim 4\pi I(LG/\sigma^2)^2$ and thus $L\sim\sigma^4$
- This is the Faber-Jackson relation

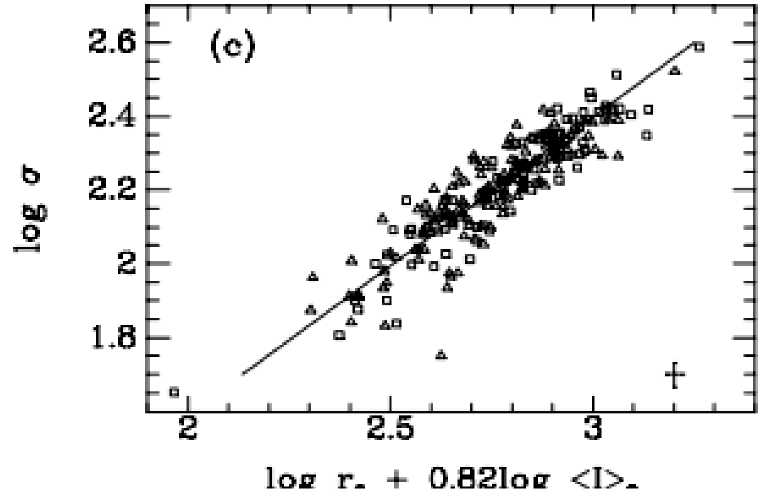
Fundamental Plane-relate their structural/dynamical status to their stellar content

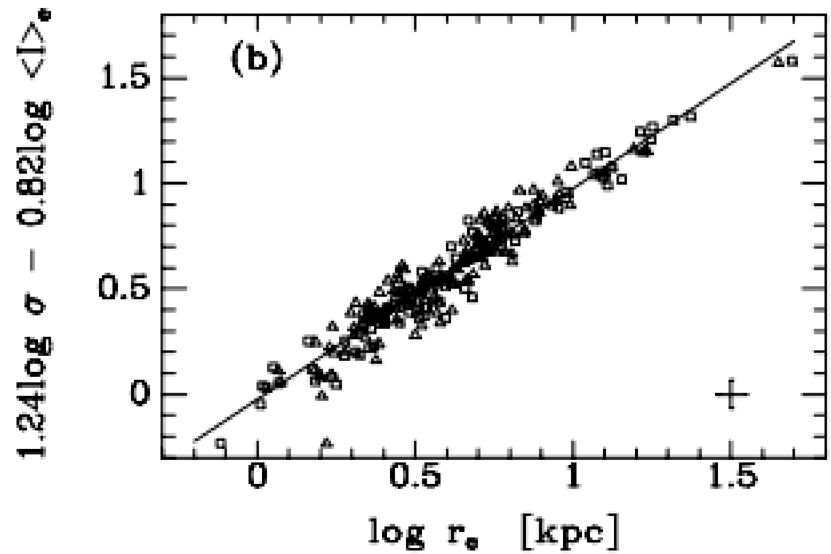
Three key observables of elliptical galaxies, effective radius Re, the central velocity dispersion σ, luminosity L (or equivalently the effective surface brightness $I_e = L/2\pi R_e^2$)

elliptical galaxies are not randomly distributed within the 3D space (R_e, σ, I_e), but lie in a plane

The existence of the FP implies that ellipticals

- are virialised systems,
- have self-similar (homologous) structures, or their structures (e.g., the shape of the mass distribution) vary in a systematic fashion along the plane, and (c)
- contain stellar populations which must fulfill tight age and metallicity constraints.





Scaling Relations

- There is a very strong relation between the size and stellar mass of normal elliptical galaxies with

  $R_{1/2} \sim M_{stellar}^{1/2}$

Notice the very high density of objects in the core of the relation

in detail (Shen et al 2009)

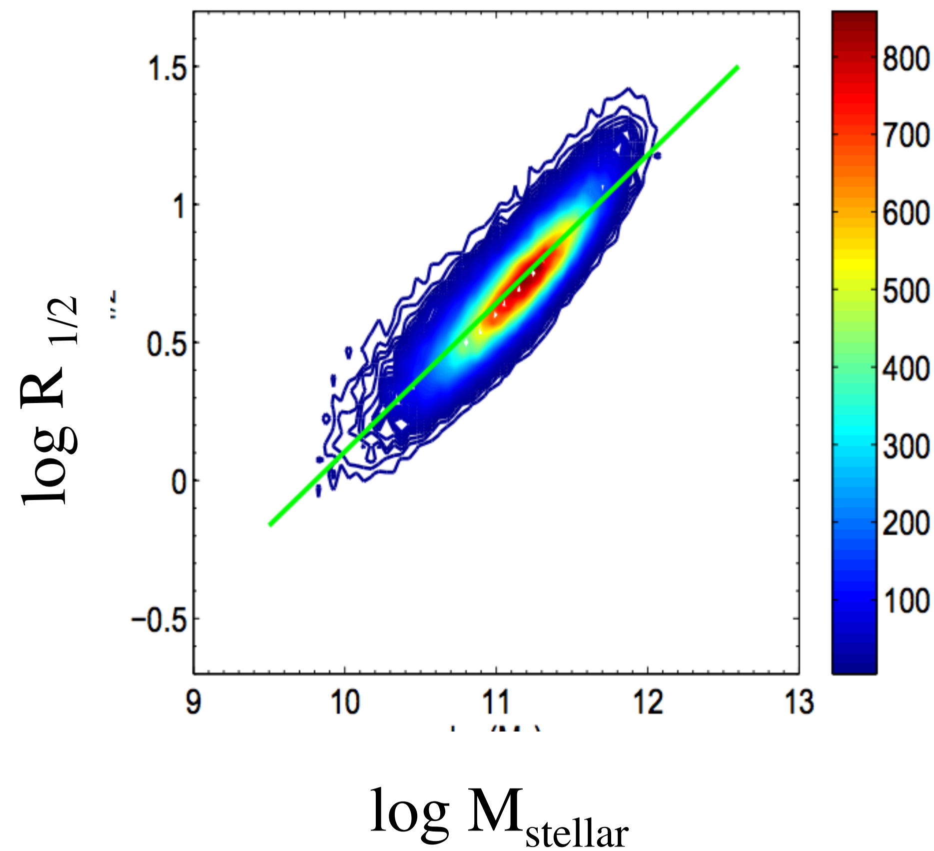
$R_{1/2} = R_e \sim 1.4(M/10^{10} M_{\odot})^{0.56}$

A test of formation theory: (MBW pg596)

If ellipticals are due to monolithic collapse correlation requires that binding energy of the gas has to become more negative by a factor ~ 7 before it forms stars, in order to explain the observed sizes

if massive ellipticals are due to 'dry' (no cold gas) mergers ;

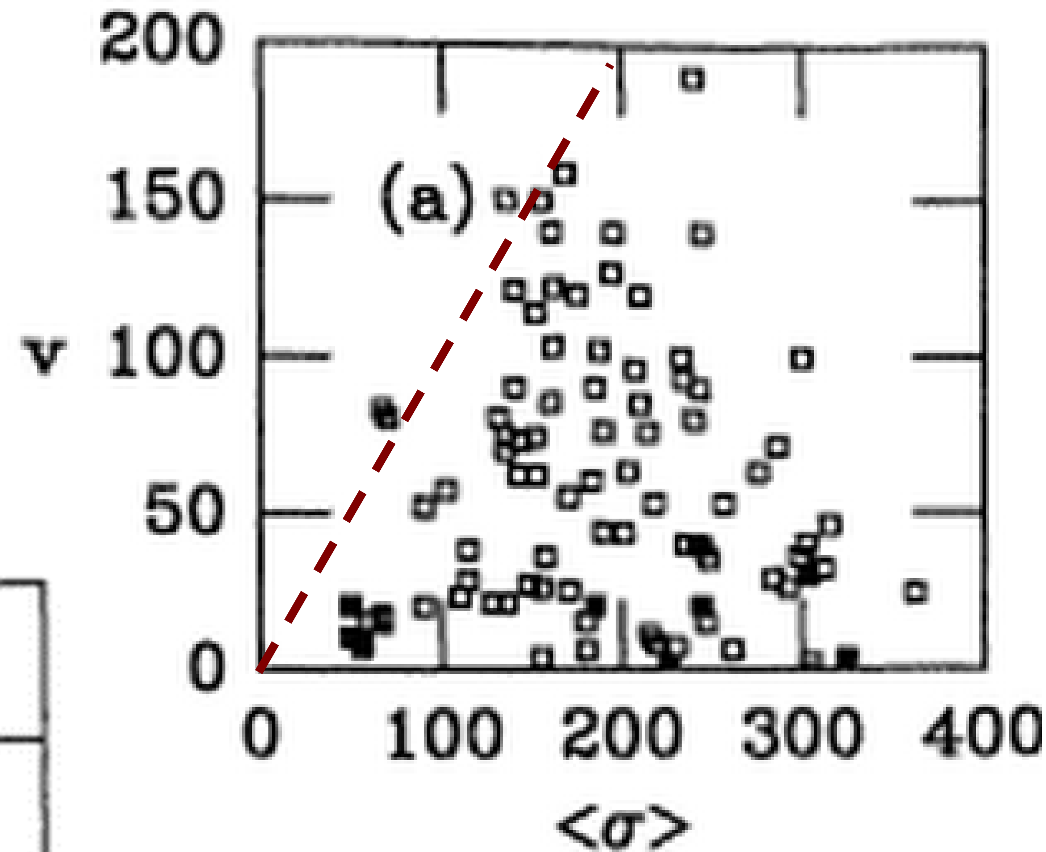
situtation is a big complex see discussion in MBW 597-600

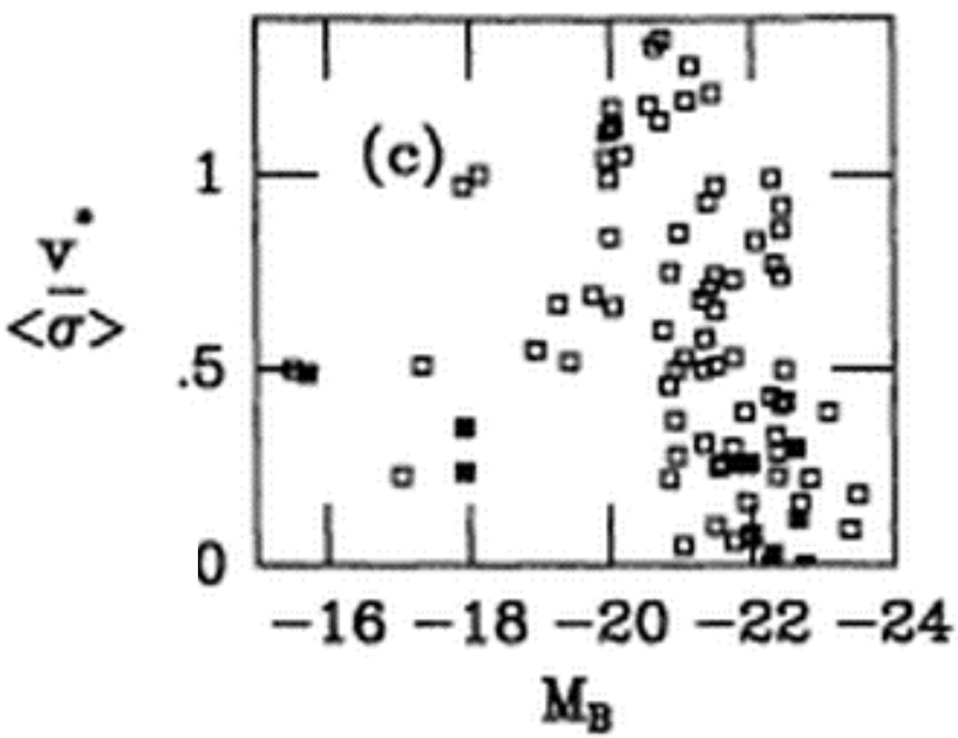


Chiosi et al 2012

Massive Ellipticals Rotate Slowly if at ALL

- At higher and higher masses the influence of rotation on ellipticals declines (e.g. V_{rot}/σ is <<1)



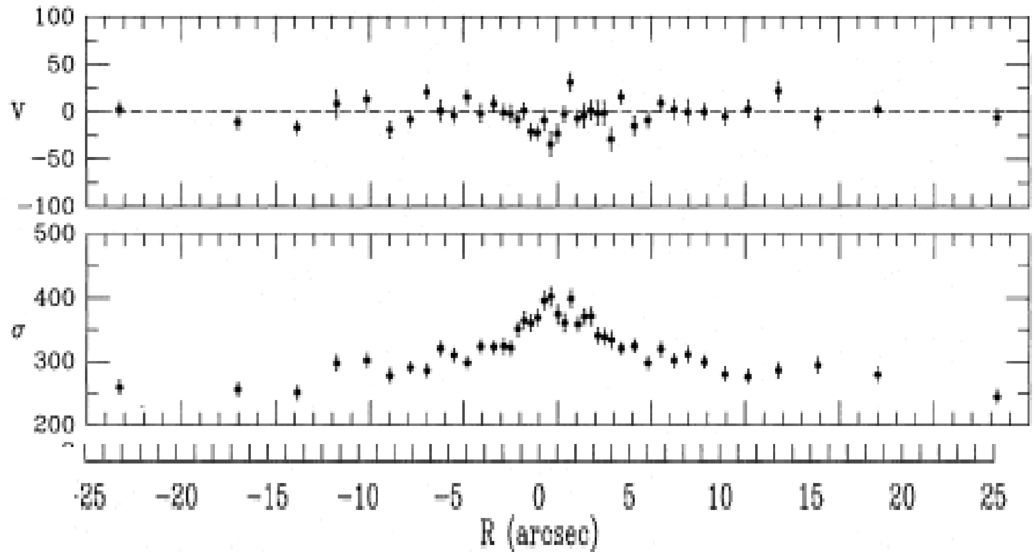


de Zeeuw and Franx 1991

Kinematics

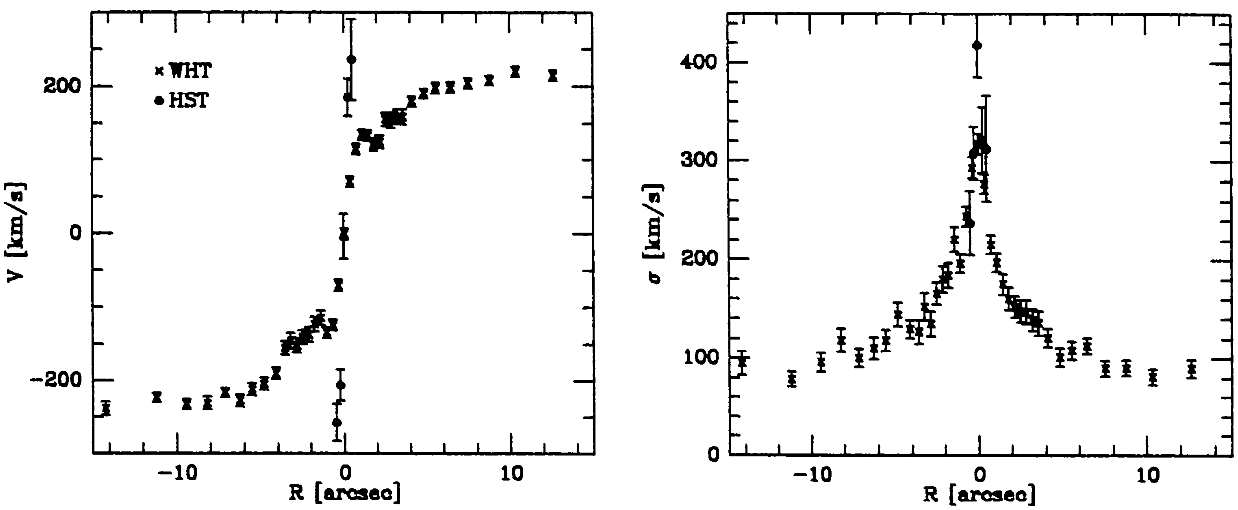
- Kinematics- the features used to measure the velocity field are due to stellar absorption lines: however these are 'blurred' by projection and the high velocity dispersion of the objects.
- Spatially resolved spectra help...
- Examples of 2 galaxies M87 and NGC 4342
  - one with no rotation and the other with lots of rotation
- The other parameter is velocity dispersion- the width of a gaussian fit to the velocity

M87van der Maerl



NGC4342

van den Bosch



For NGC4342 its observed flattening is consistent with rotation

How do we use observable information to get the masses??

Observables:

- Spatial distribution and kinematics of "tracer population(s)", which may make up
  - all (stars in globular clusters?)
  - much (stars in elliptical galaxies?) or
  - hardly any (ionized gas in spiral galaxies)

of the "dynamical" mass.

- In external galaxies only 3 of the 6 phase-space dimensions, are observable: $x_{proj}, y_{proj}, v_{LOS}$!

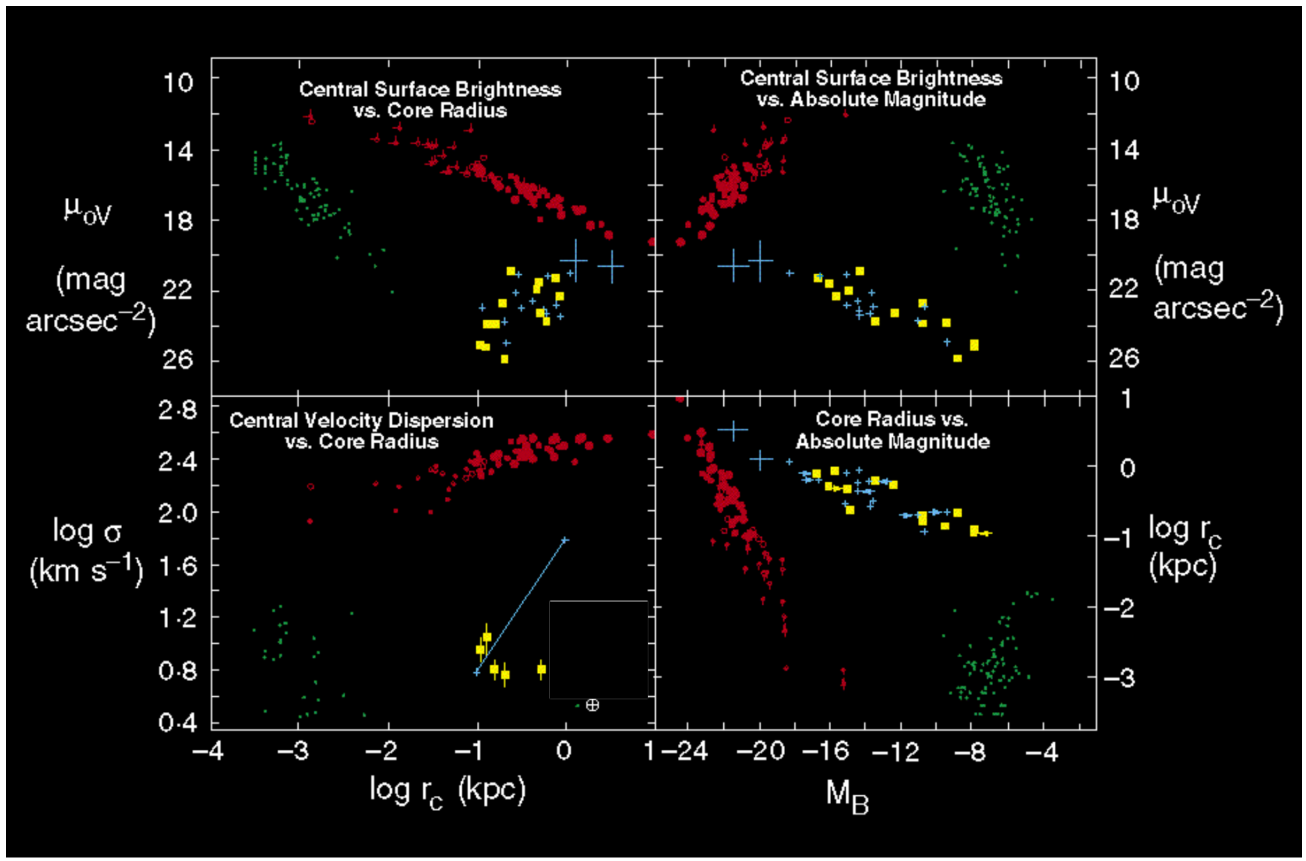
Note: since $t_{dynamical} \sim 10^8$ yrs in galaxies, observations constitute an instantaneous snapshot.

…

Kinematics

- As stressed in S+G eg 6.16 and MBW 13.1-13.7 the observed velocity field over a given line of sight (LOS) is an integral over the velocity distribution and the stellar population (e.g. which lines one sees in the spectrum)
- One breaks the velocity into 2 components
  - a 'gaussian' component characterized by a velocity dispersion- in reality a bit more complex
  - a redshift/blue which is then converted to rotation
  - The combination of surface brightness and velocity data are used to derive the potential- however the results depend on the models used to fit the data - no unique decomposition

- 3 key observables of elliptical galaxies,
- the effective radius R_e, the central velocity dispersion σ, and the luminosity L (or equivalently the effective surface brightness $I_e = L/2\pi R^2_e$) relate their structural/dynamical status to their stellar content.
- elliptical galaxies are *not randomly distributed within the 3D space* (R_e, σ, I_e), but lie in plane, thus known as the fundamental plane (FP), with $R_e \sim \sigma^a I_e^b$
- collapsing the FP over the (R_e, I_e) coordinate plane generates the Kormendy relation
- a projection over the (σ, $L = 2\pi I_e R^2_e$) plane generates the Faber-Jackson relation (Faber & Jackson 1976)



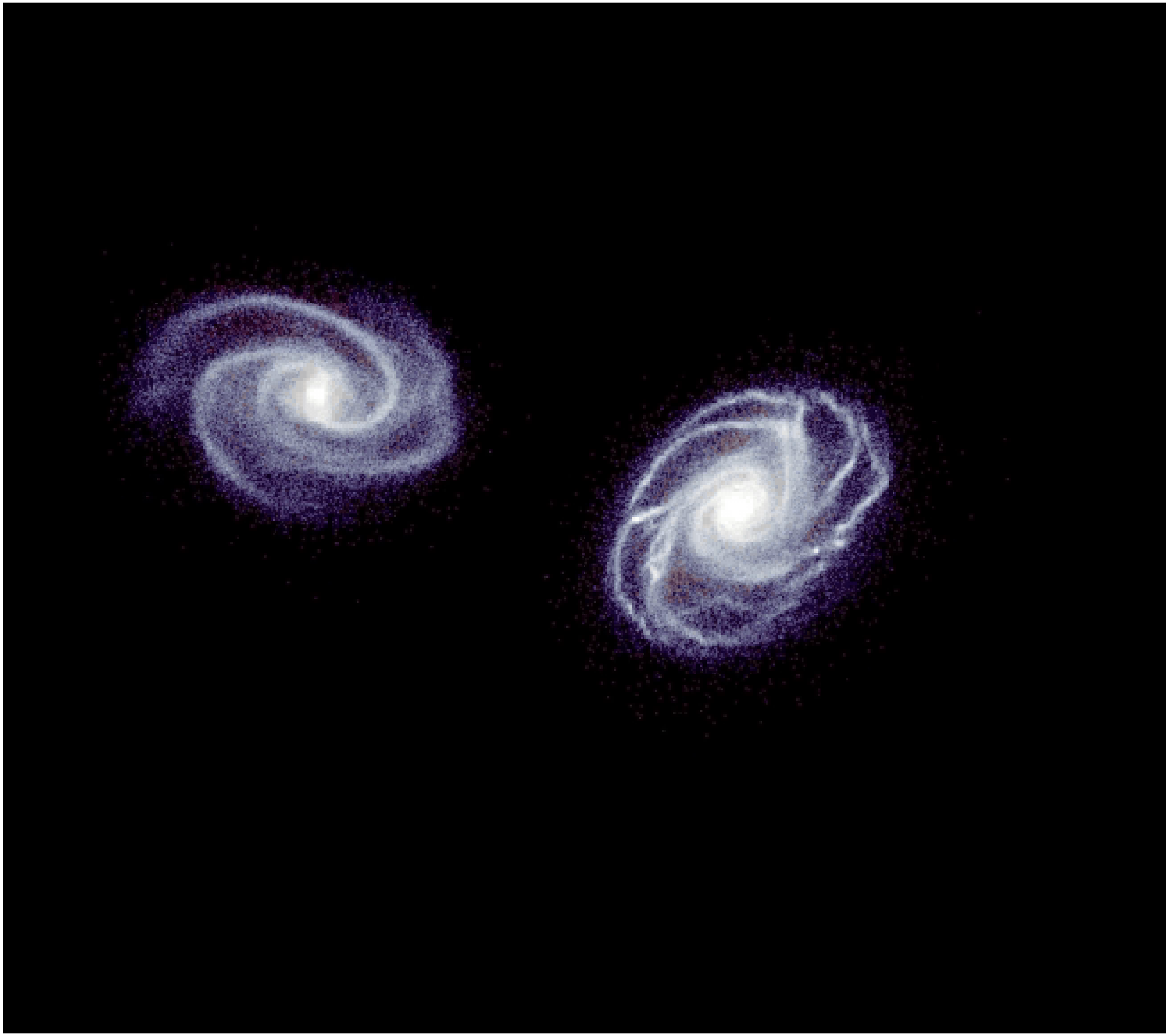
What Does Fundamental Plane Tell US

- the existence of the FP is due to the galaxies being in virial equilibrium (e.g. Binney & Tremaine 2008) and that the deviation (tilt) of the coefficients from the virial predictions $R_e=\sigma^2/\Sigma_e$, (is the stellar surface brightness at R_e) are due to a smooth variation of mass-to-light ratio M/L with mass
- The FP showed that galaxies assemble via regular processes and that their properties are closely related to their mass.
- The tightness of the plane gives constraints on the variation of stellar population among galaxies of similar characteristics and on their dark matter content
- The regularity also allows one to use the FP to study galaxy evolution, by tracing its variations with redshift
- Visible matter densities decrease with decreasing galaxy mass, consistent with the progressive loss of more and more baryons as gravitational potential wells get shallower
- (Cappellari et al 2012)

The Big Picture of Elliptical Galaxy Formation

- Hierarchical clustering leads to galaxy mergers that scramble disks and make ellipticals
- Merger progenitors usually contain gas; gravitational torques drive it to the center and feed starbursts
- quasar energy feedback has a major effect on the formation of bright ellipticals but not faint ellipticals

- This helps to explain why supermassive BHs correlate with bulges but not disks
- bulges and ellipticals are made in mergers, but disks are not.



Shells Around Elliptical Galaxies (MBW sec 13.3.5)

- Indication of mergers- the shells are at the apogee of the highly elliptical orbits
- remnants of a minor merger between a massive elliptical and a lower mass disk-like galaxy.
- The main requirements are that the disk-shaped galaxy be “cold”, and

that the elliptical is much more massive than its companion.

The smaller galaxy’s stars fall into the center of the galaxy and phase wrap, e.g. form alternating outward-moving density waves made of the disk galaxy’s particles near the maximum excursions of their largely radial orbits in the rigid potential

•The particles will oscillate in the potential well of the elliptical and form a sharp crest at their radii of turnaround.

A spread in the periods will result from the initial spread in energy, so that multiple shells will form between a maximum and a minimum radius, defined by the maximum and minimum energies of the particles in the disk.

Summary of Last Lecture

- Fundamental plane connects luminosity, scale length, surface brightness, stellar dynamics and chemical composition
  - \- Faber Jackson relation $L \sim \sigma^4$

  – More luminous galaxies have deeper potentials

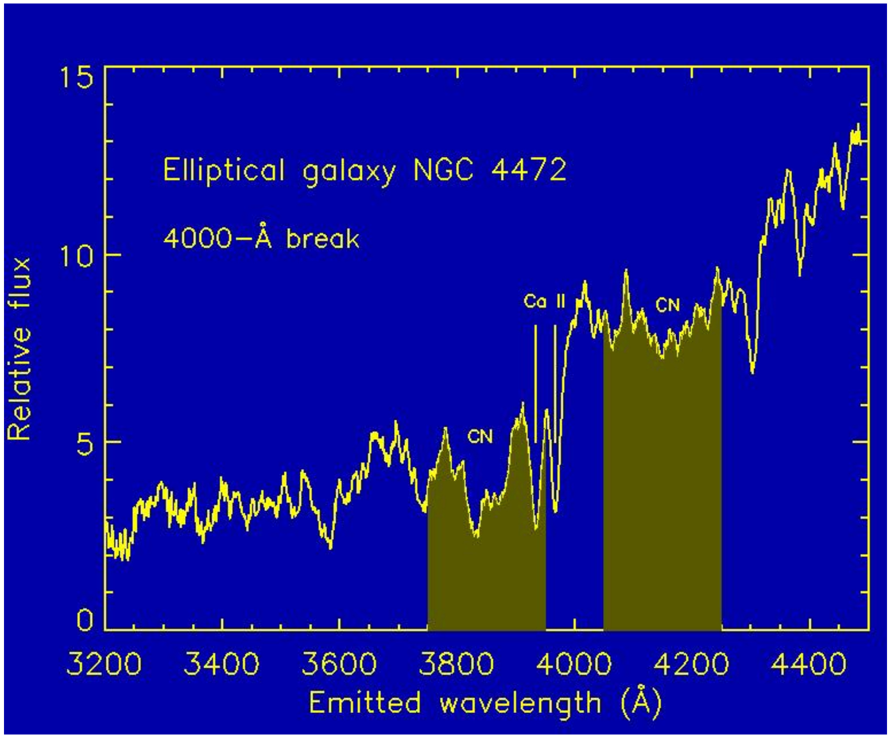
  follows from the Virial Theorem if M/L is constant

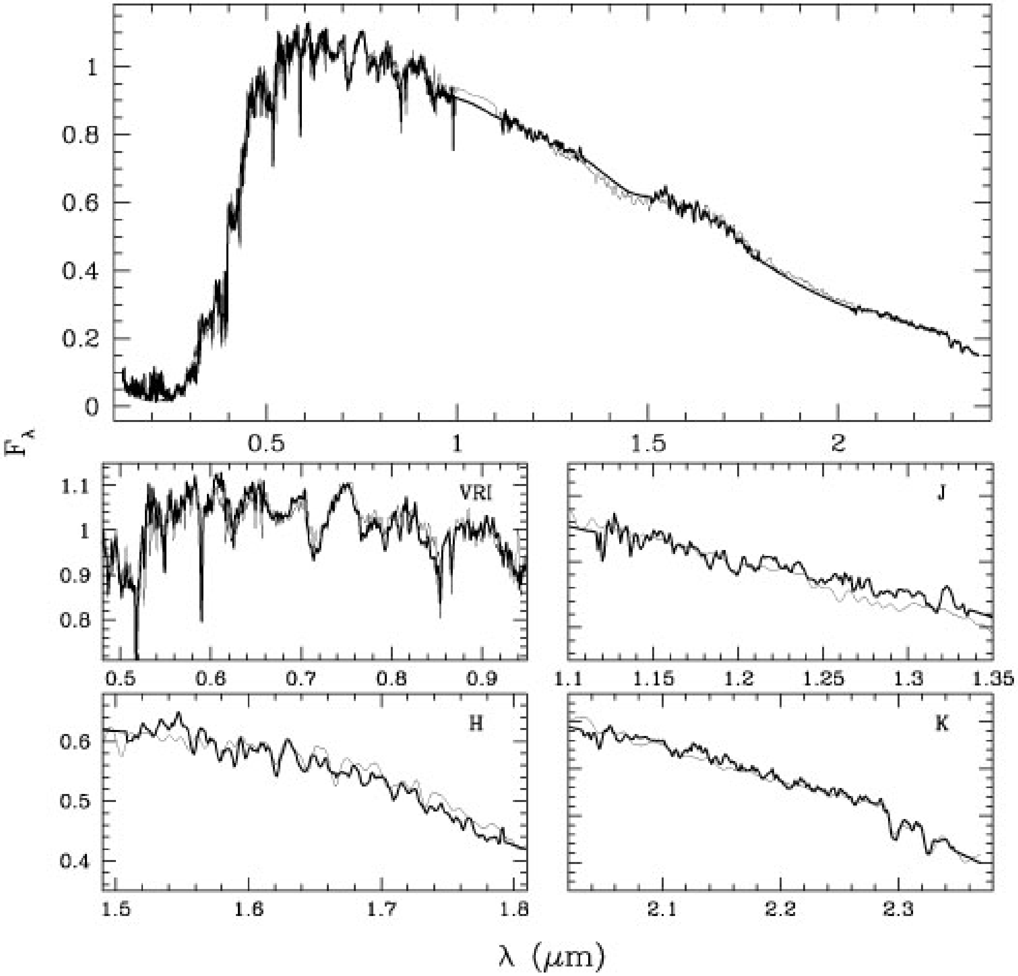
- Kinematics- massive ellipticals rotate very slowly, lower mass ones have higher ratio of rotation to velocity dispersion

Spectrum of Ellipticals

- Optical and near IR spectrum dominated by old stars-how do we know this?
  - colors
  - spectrum

'standard' optical colors UBVRI are not very sensitive to age, metallicity of old stellar pops



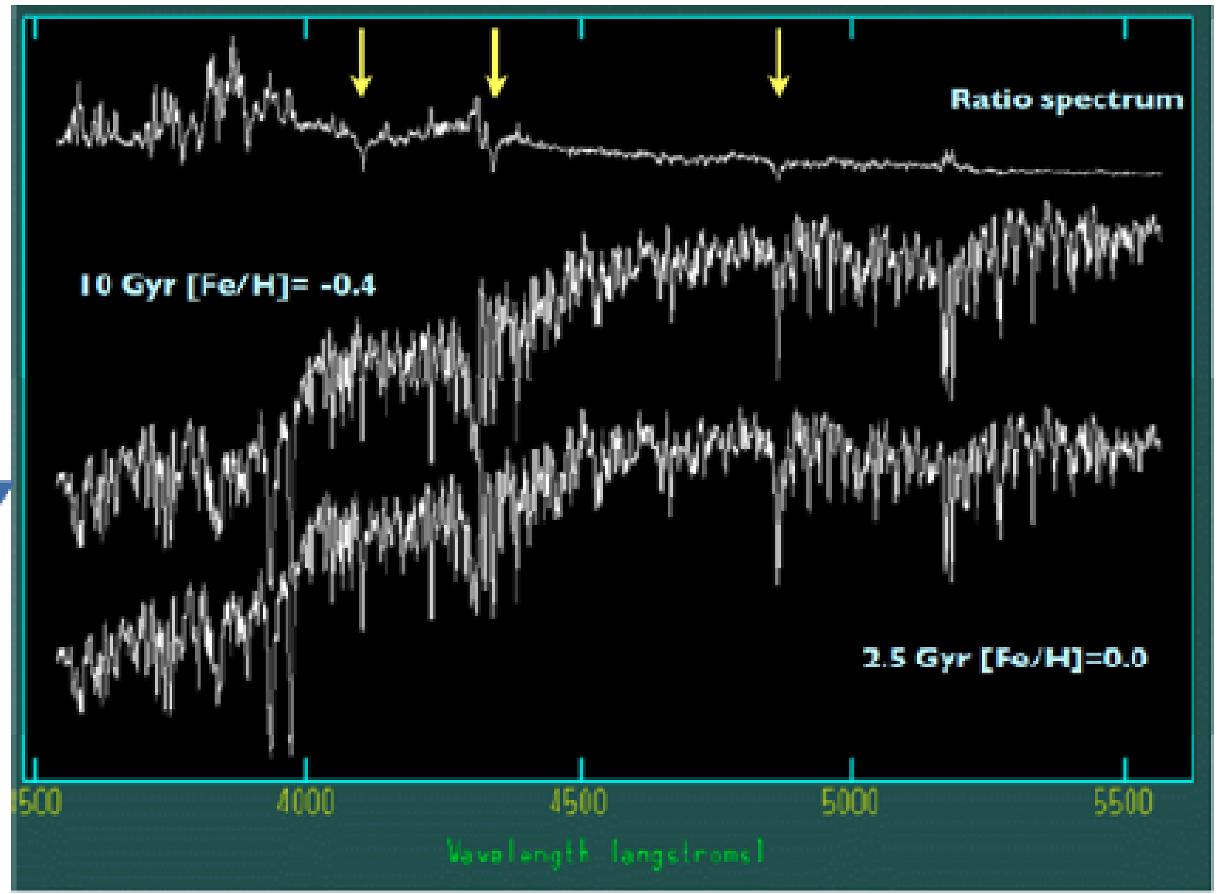


see GuyWorthy's web page http://astro.wsu.edu/worthey/dial/dial_a_model.html

Age Metallicity Degeneracy

- Optical spectra of ETGs have absorption features whose strength depends on the distributions of stellar ages, metallicities and abundance ratios
- For old stellar populations there is a strong degeneracy twixt age and metallicity
- Elemental abundance is solar or super-solar and is enriched in α elements such as Mg

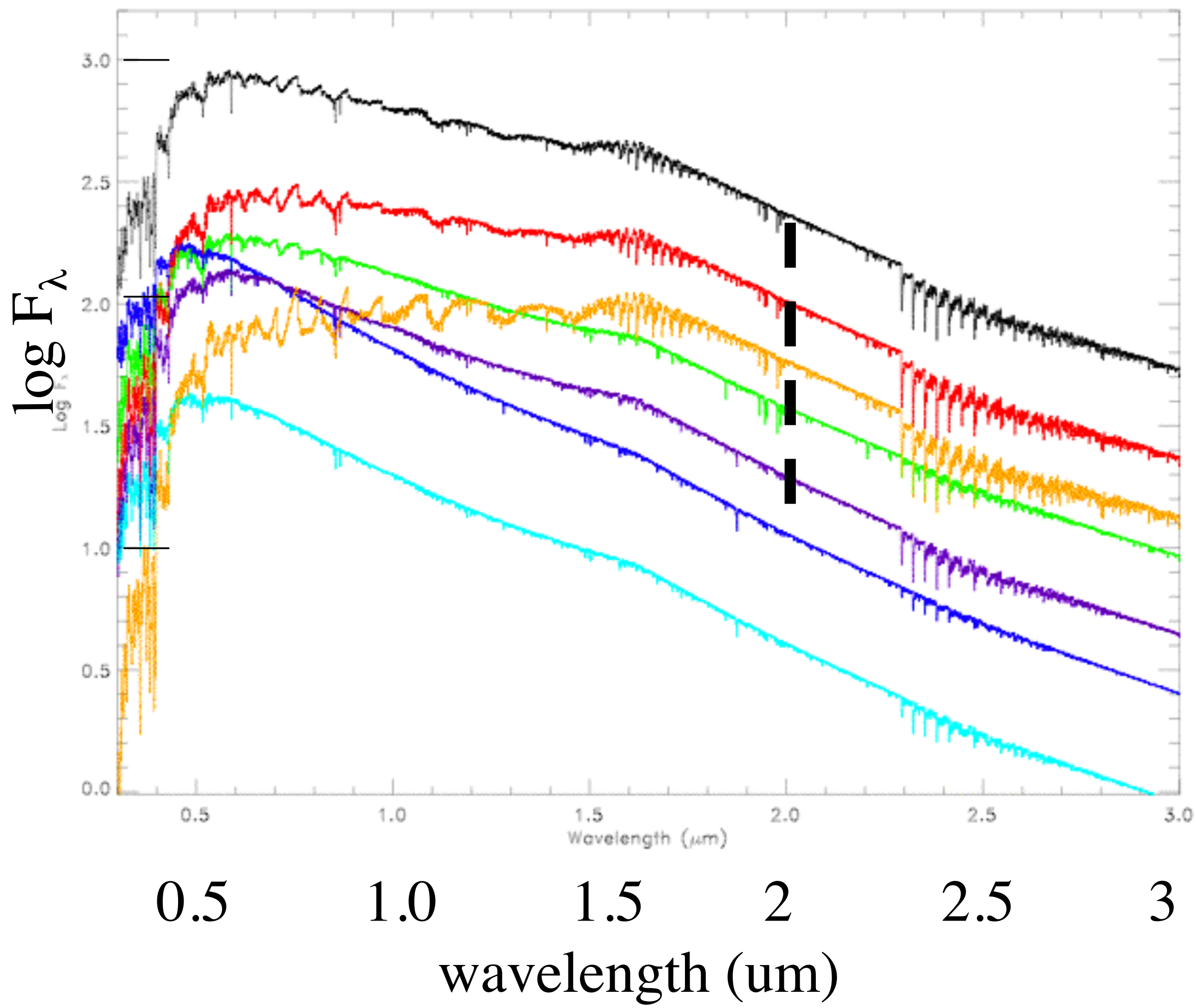
–age, metallicity and [α/Fe]– correlate strongly with σ,



Vazdekis et al. (2007) models from MILES library

Synthetic Spectum of 16Gyr SSP- Kroupa IMF

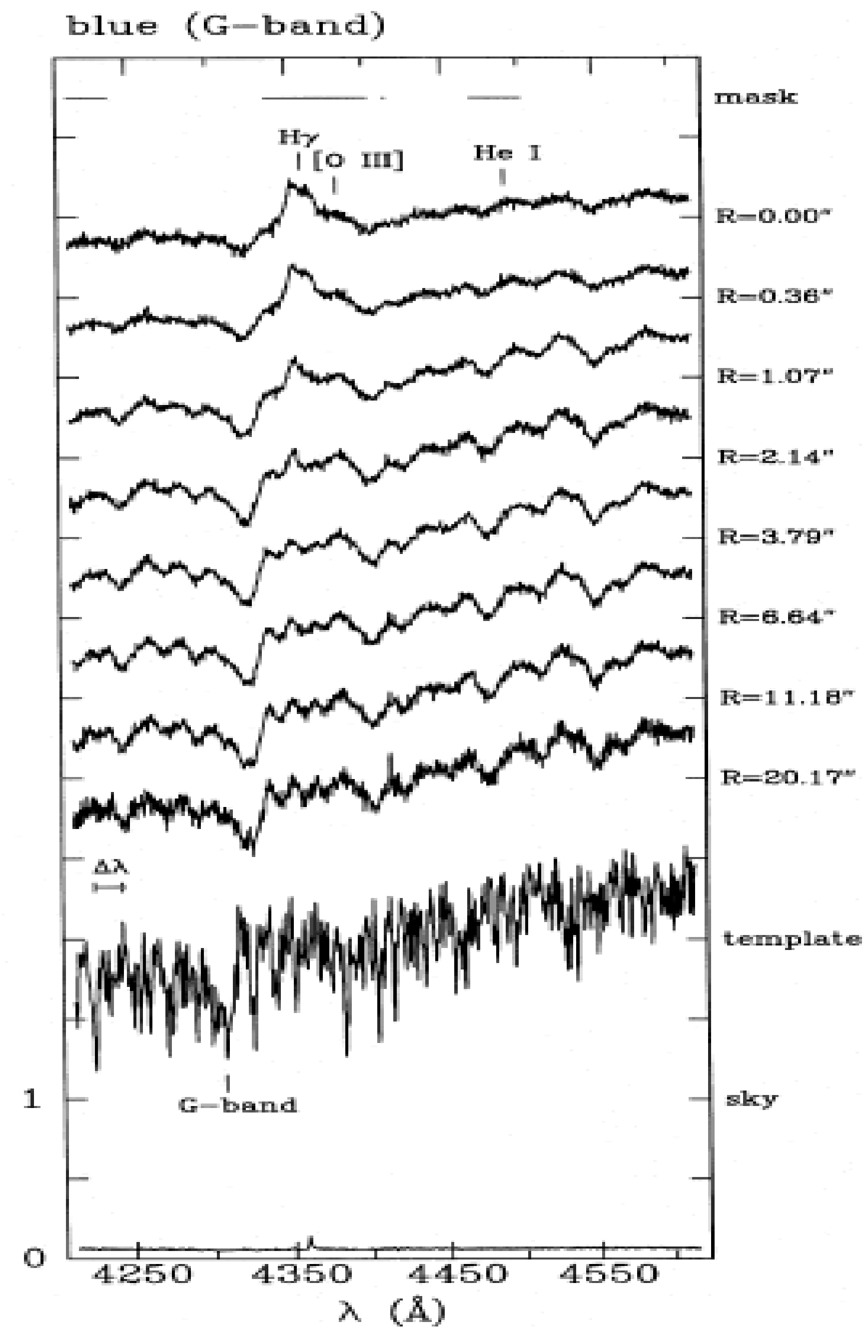
- Black is total
- Red is the red giant branch
- lower main sequence green
- Yellow is AGB (argh!)
- Main point is that in the optical most of the light is from giants which have weak spectral features



Analysis of Spectral Data

- One convolves a template spectra of a star with the observed spectra and fit for a width and shift- the shift is due to both the Hubble velocity and galaxy rotation.
- With careful choice of spectral band these results are not very sensitive to the template star chosen.
- This allows estimates of the stellar population

Spectra at increasing radii in an elliptical galaxy - allow measurement of velocity field and estimates of metallicity and age



X-ray Emission

- The temperature of the hot gas is set primarily by the depth of the potential well of the galaxy
- The emission spectrum is bremmstrahlung +emission lines from the K and L shells of the abundant elements
- The ratio of line strength to continuum is a measure of the abundance of the gas.

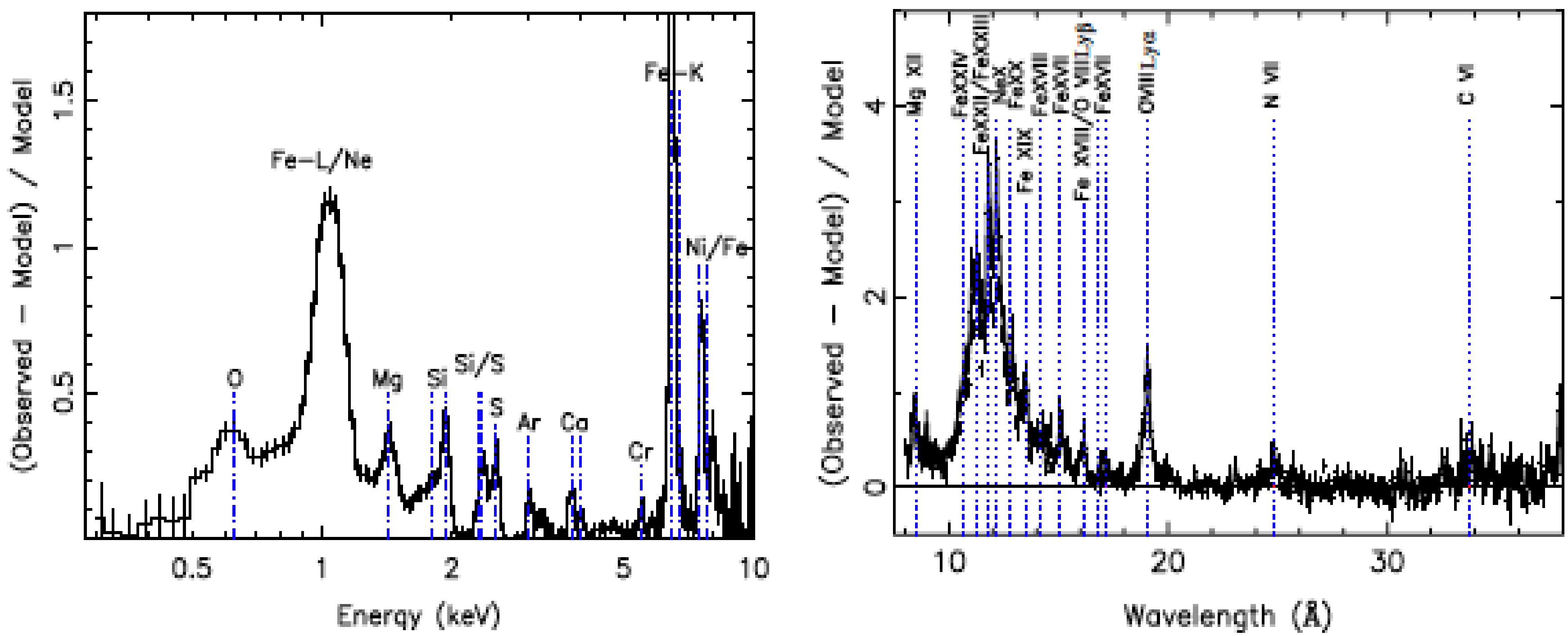
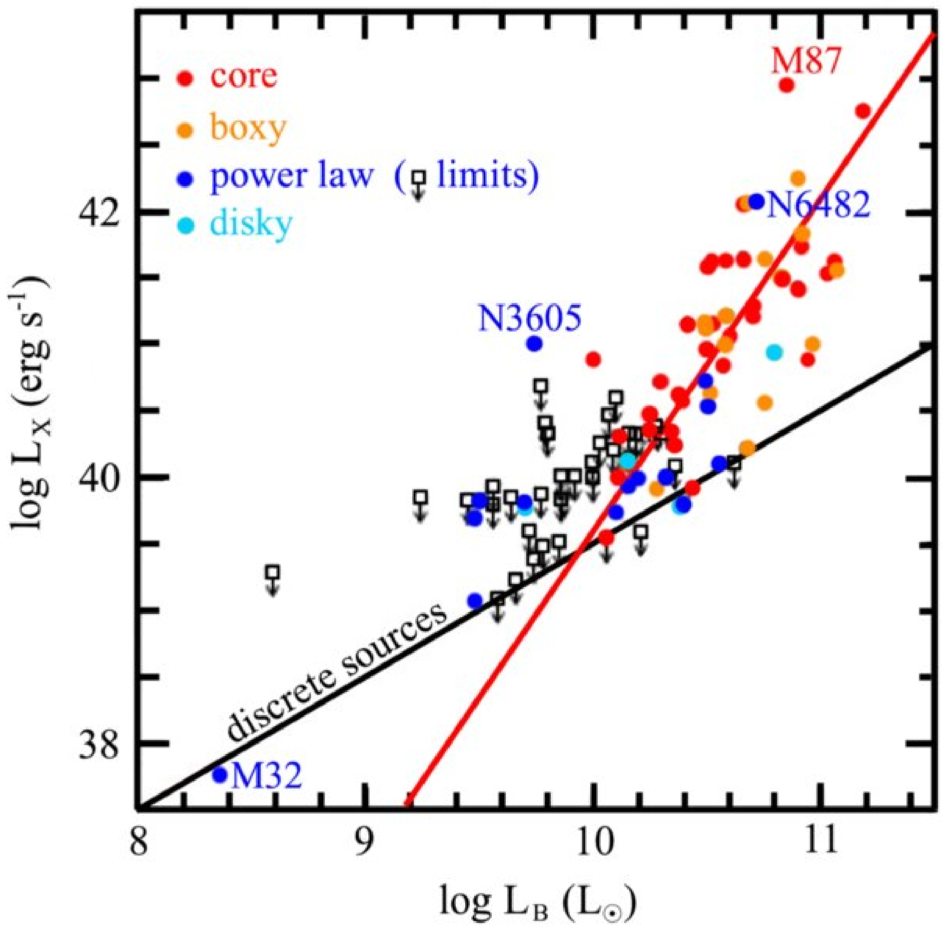


Fig. 31 *Left panel* The line spectrum of the cluster 2A 0335+096, as observed with *XMM-Newton* EPIC

X-ray Emission in Ellipticals

- 2 sources: x-ray binaries and hot gas. The ISM in most ellipticals is dominated by hot, kT~10^{6-7} K gas.
- The x-ray binary population is LMXBs (low mass x-ray binaries)
- Their x-ray spectra are very different.

- there is a relation between galaxy morphology and x-ray emission: *cored galaxies are x-ray hot gas luminous* - power-law galaxies do not contain significant X-ray-emitting gas.
- M_{gas}/M_{*}~0.01-0.001 100x less than in MW spirals - takes only 10^8-10^{10} yrs to accumulate this gas from normal stellar mass loss - gas must be dynamic



Use of X-rays to Determine Mass

- X-ray emission is due to the combination of thermal bremmstrahlung and line emission from hot gas
- The gas should be in equilibrium with the gravitational potential (otherwise flow out or in)
- density and potential are related by Poisson's equation

  $\nabla^2\phi = 4\pi\rho G$
- and combining this with the equation of hydrostaic equil

  $$\nabla \bullet (1/\rho \nabla P) = -\nabla^2\phi = -4\pi G\rho$$

gives for for a spherically symmetric system

$(1/\rho_g)\, dP/dr = -d\phi(r)/dr = GM(r)/r^2$

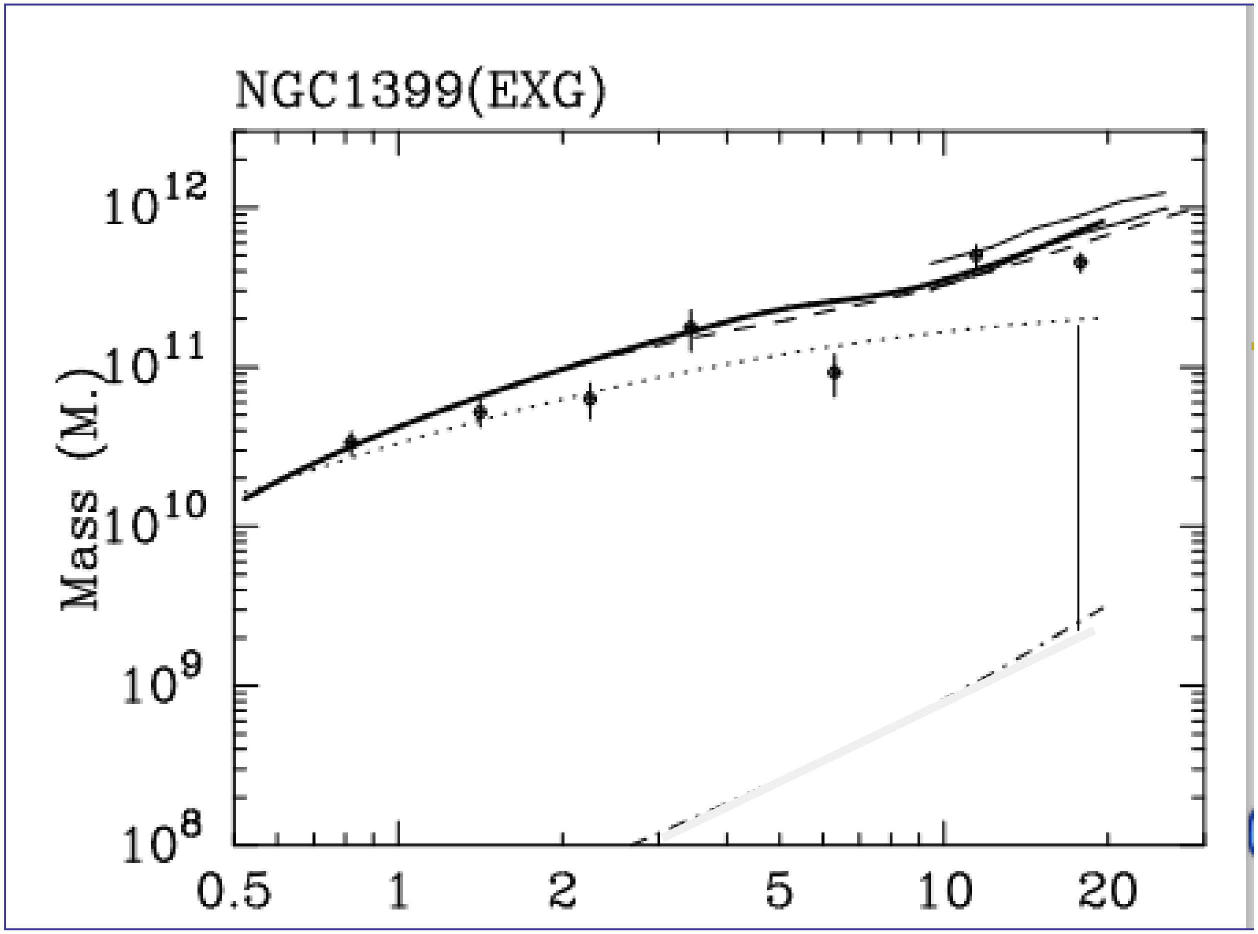
With a little algebra and the definition of pressure - the total cluster mass (dark and baryonic) can be expressed as

$$M(r) = kT_g(r)/\mu G m_p)\mathbf{r}\ (d\ln T/dr + d\ln\rho_g/dr)$$

k is Boltzmans const, μ is the mean mass of a particle and m_H is the mass of a hydrogen atom
Every thing is observable
The temperature T_g from the spatially resolved spectrum
The density ρ_g from the knowledge that the emission is due to bremmstrahlung
And the scale size, **r**, from the conversion of angles to distance

NGC1399- A Giant Elliptical

- Solid line is total mass
- dotted is stellar mass
- dash-gas mass is gas
- In central regions gas mass is ~1/500 of stellar mass but rises to 0.01 at larger radii
- Gas extends beyond stars (like HI in spirals) and thus the ratio is not meaningful at larger radii



•Use hydrostatic equilibrium to determine mass **$\nabla P=-\rho_g \nabla \phi(r)$** where $\phi(r)$ is the gravitational potential of the cluster (which is set by the distribution of matter) P is gas pressure and **ρ_g** is the gas density

Dynamics of Ellipticals

- More complex than spirals- 3D system (1 velocity and 2 position degrees of freedom can be measured).

- The prime goal of dynamical measurements is to determine the mass of the system as a function of position (mostly radius) and thus the mass-light ratio of the stars. Unfortunately the data are not directly invertable and thus one must resort to models and fit them.
- Most recent models have been motivated by analytic fits to detailed dark matter simulations derived from large scale cosmological simulations.

- Additional information has been provided by
  - gravitational lensing (only 1 in 1000 galaxies and distant),
  - velocity field of globular clusters
  - use of x-ray hot gas halos which helps break much of the degeneracies.
  - Hot gas and globular velocities can only be measured for nearby galaxies (D<40Mpc) and only very massive galaxies have a measurable lensing signal.

Dark Matter in Ellipticals

- It is rather difficult to determine whether dark matter is important in the central regions of ellipticals with just velocity and surface brightness data- lensing breaks the degeneracies
- Next lecture will be on dark matter.

Mass Determination

- for a perfectly spherical system one can write the Jeans equation as
- $(1/\rho)d(\rho\langle v_r\rangle^2)/dr+2\beta/r\langle v_r\rangle^2=-d\phi/dr$
- where ϕ is the potential and β is the anisotropy factor $\beta=1-\langle v_\theta\rangle^2/\langle v_r\rangle^2$
- since $d\phi/dr=GM_{tot}(r)/r^2$
- one can write the mass as
- $M_{tot}(r)=r/G\langle v_r\rangle^2\ [d\ln\rho/d\ln r+d\ln/\langle v_r\rangle^2/d\ln r+2\beta]$
- expressed in another way

$$M(r)=\frac{V^2r}{G}+\frac{\sigma_r^2r}{G}\left[-\frac{d\ln\nu}{d\ln r}-\frac{d\ln\sigma_r^2}{d\ln r}-\left(1-\frac{\sigma_\theta^2}{\sigma_r^2}\right)-\left(1-\frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

•Notice the nasty terms

•V_r is the rotation velocity σ_r $\sigma_{\theta,}$ σ_ϕ are the 3-D components of the velocity dispersion ν is the density of stars

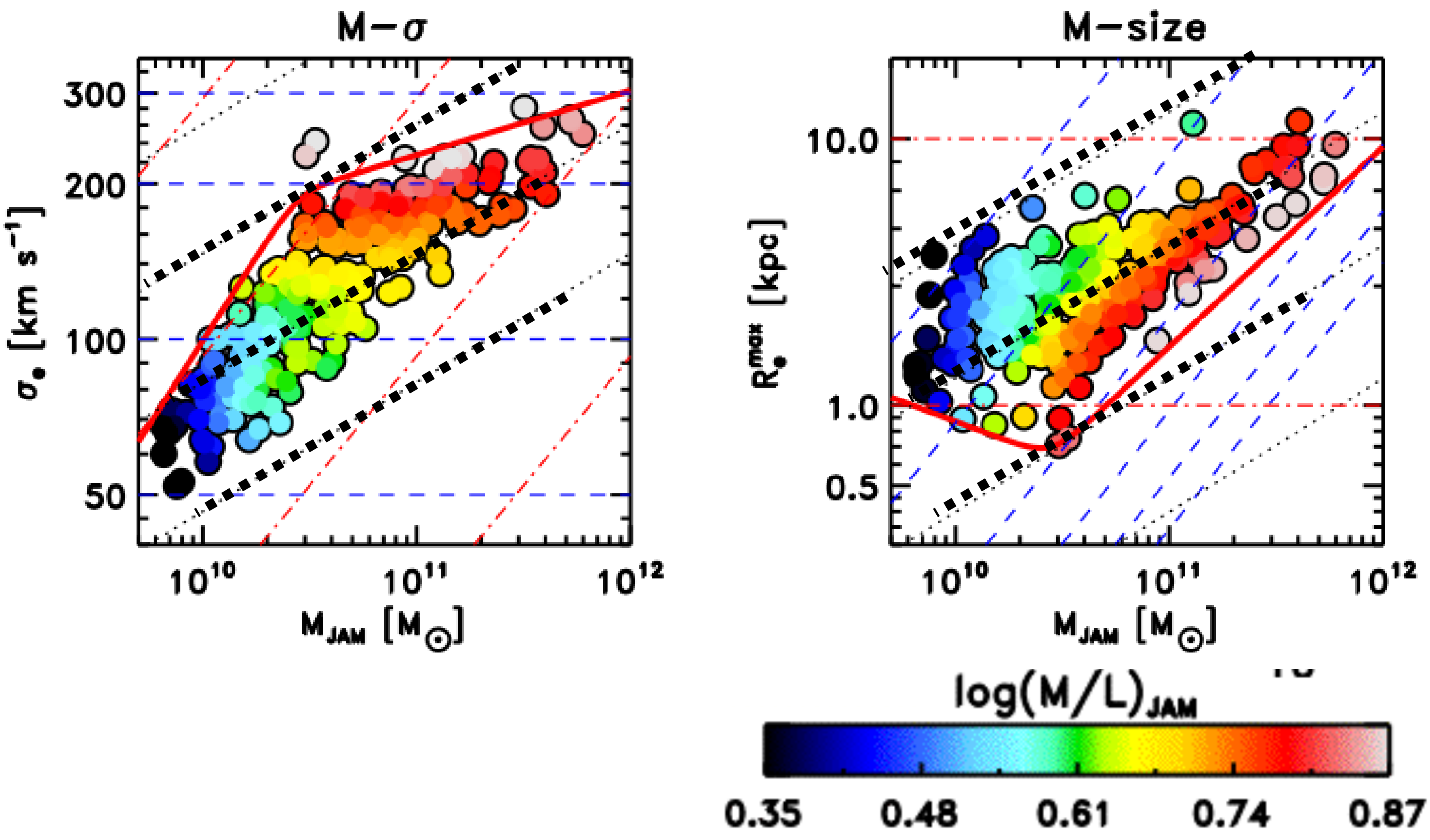
•All of these variables are 3-D; we observe projected quantities !

•The analysis is done by generating a set of stellar orbits and then minimizing

•Rotation and random motions (dispersion) are both important.

Detailed Analysis of Ellipticals

- More massive galaxies are larger and have high velocities and higher M/L- but not exactly as the virial theorm would predict (Black lines)



- $M(R)=(V^2r/G)+(r\sigma^2_r/G)[-d\ln\rho/d\ln r - d\ln\sigma^2_r/d\ln r-(1-\sigma^2_\theta/\sigma_r^2)-(1-\sigma^2_\phi/\sigma^2_r)]$
- where V is the rotation velocity and are the radial (σ_r) and $\sigma_{\theta,}$, σ_ϕ are the angular components of the velocity dispersion

$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1-\frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1-\frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

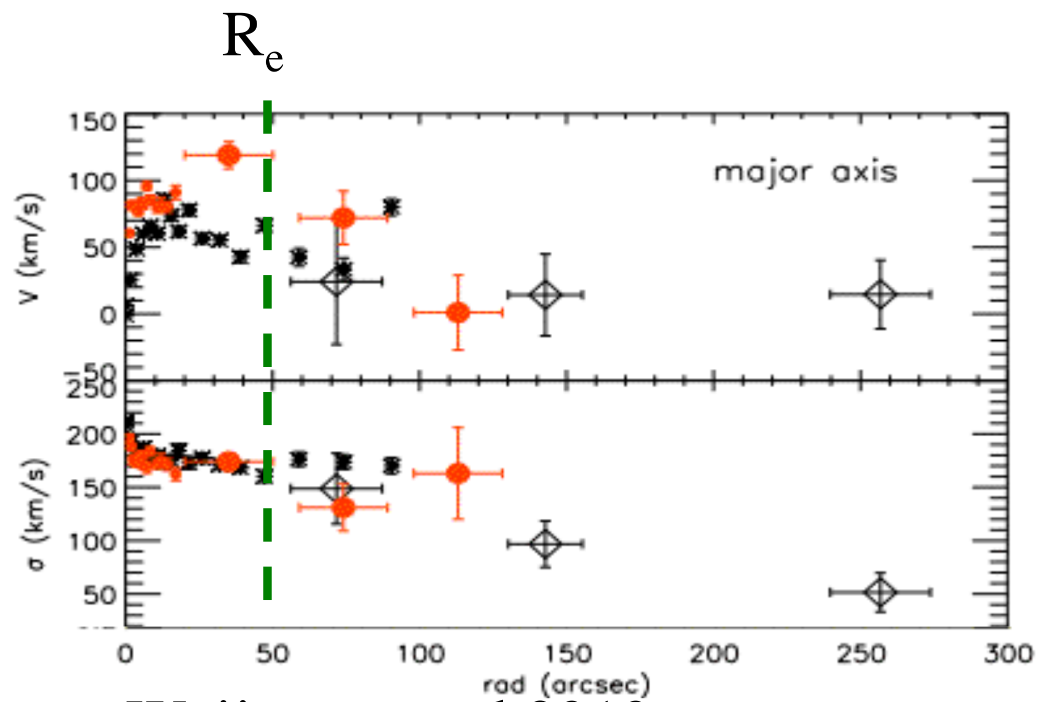
Modeling

- A key degeneracy is in the deprojection of the observed surface brightness into a three dimensional stellar mass distribution, which is irrecoverable.
- current data provide at most a three-dimensional observable (an integral-field data cube), the minimum requirement to constrain the orbital distribution, which depends on three integrals of motion, for an assumed axisymmetric potential and known light distribution.
- get a dramatic increase in the non-uniqueness of the mass deprojection expected in a triaxial rather than axisymmetric distribution
- the data do not contain enough information to constrain additional parameters, like the dark matter halo shape and the viewing angle

Detailed Fit for only a Few Objects at Large Radii

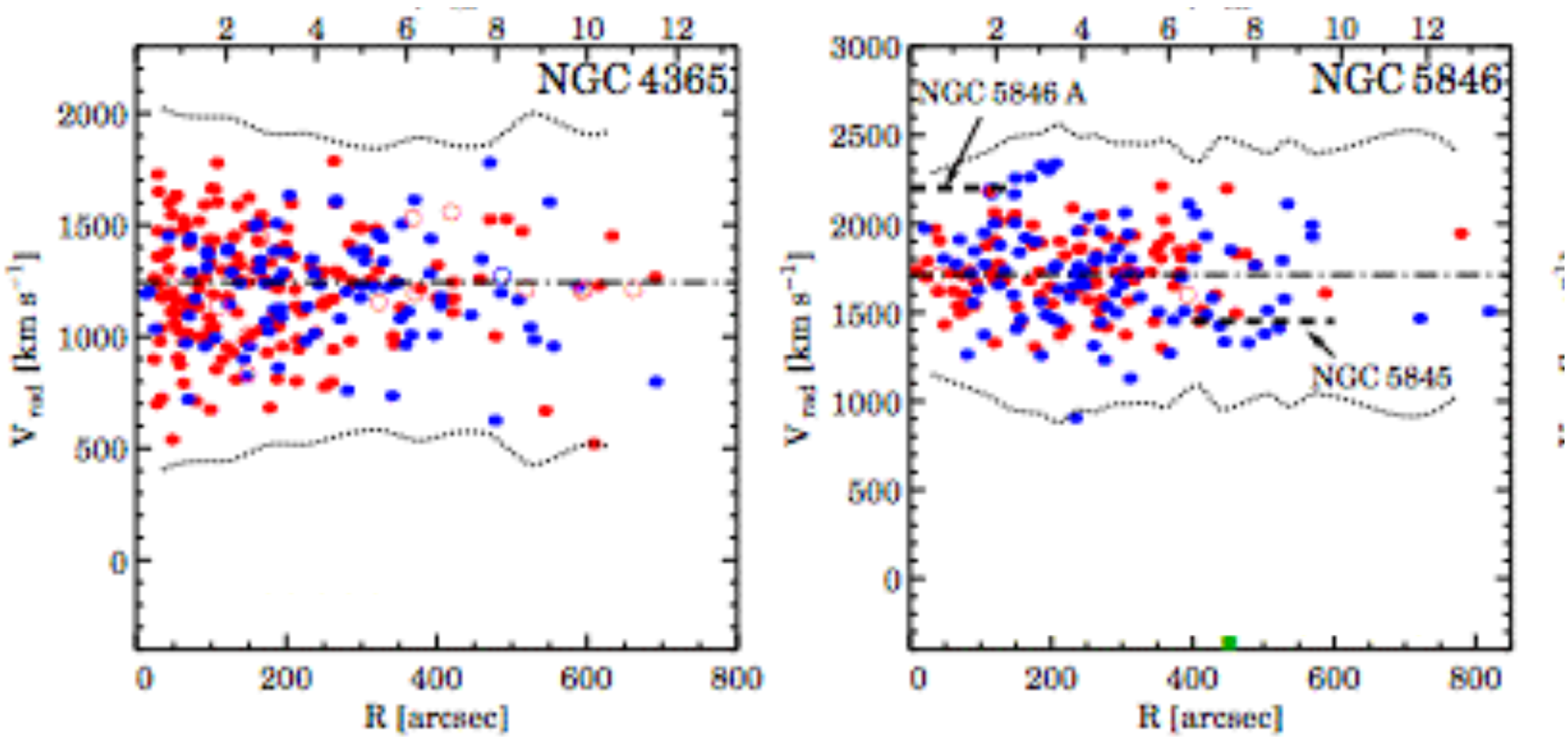
In order to fit the observed mildly declining or constant velocity dispersion profile without invoking dark matter at large radii, the orbits have to be tangentially anisotropic, while adding a dark halo results in more radially anisotropic orbits (!) - this is not seen requiring dark matter.

However the shape of the potential is not well determined

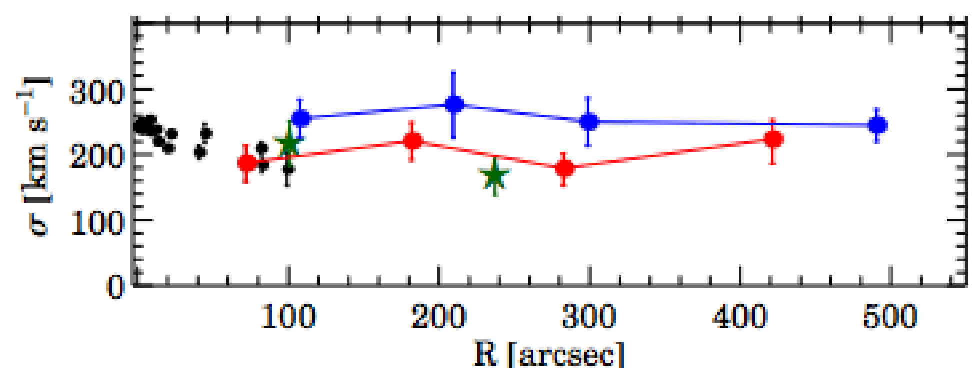


Weijmans et al 2010

Velocity field of globular clusters



- Some of the galaxies show a very flat velocity dispersion profile for the globulars out to large radii- evidence for dark matter or fine tuned anisotropy profiles



Mass Determination

- Try to get the velocity dispersion profiles as a function of r, going far from the center- this is technically very difficult since the star light gets very faint.
- Try to use other tracers such as globular clusters, planetary nebulae, or satellite galaxies; however suffer from same sort of degeneracies as the stars.
- See flat profiles far out- either a dark matter halo or systematic change in β with radius.
- General idea $M \sim k r \sigma^2/G$ where k depends on the shape of the potential and orbit distribution etc ; if one makes a assumption (e.g. SIS or mass is traced by light) one can calculate it from velocity and light profile data. k=0.3 for a Hernquist potential, 0.6 in numerical sims.
- General result:DM fraction increases as R_e, σ, n and M* increase, but the DM density decreases as R_e, n and M* increase

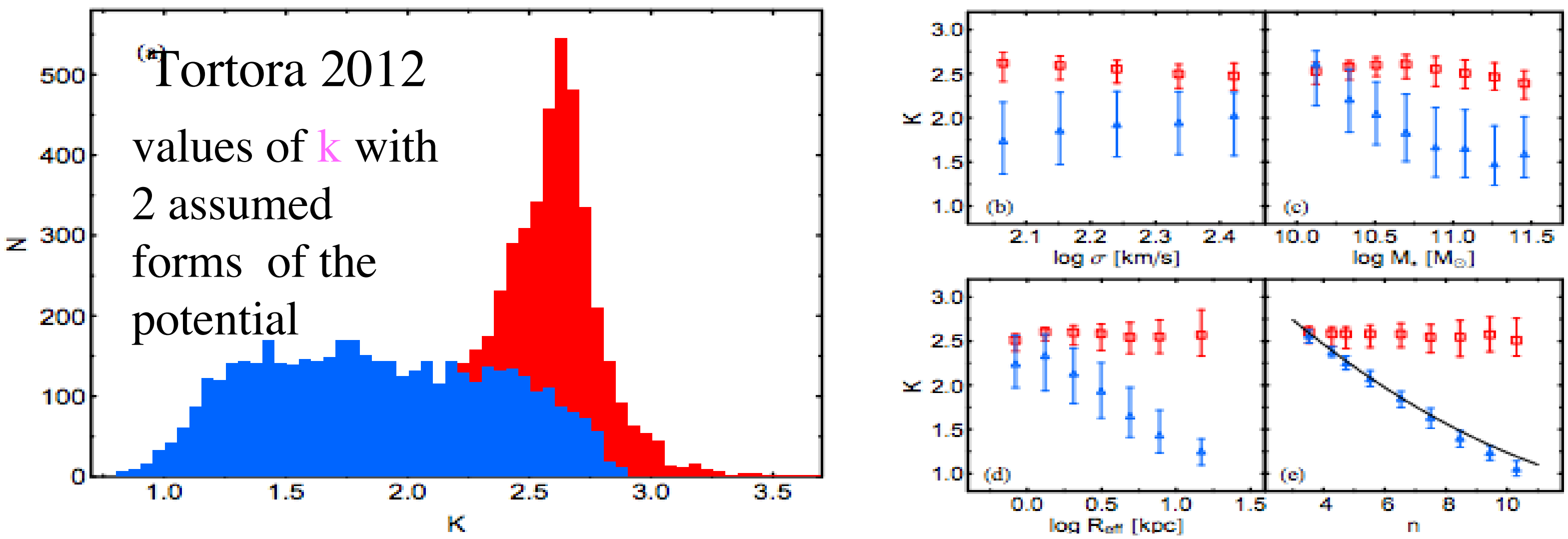


Figure 1. *Panel (a).* Distributions of K for SIS and const-M/L mass models (see Eq. (1)). *Panels (b-e).* Median value of K as a function of σ (b), $M_\star$ (c), $R_{\rm eff}$ (d), and n (e). Median values, with error bars showing 25–75 per cent scatter. Red and blue colours refer to SIS and const-M/L models, respectively. The black curve in panel (e) is taken from Bertin et al. (2002).

Viral Plane

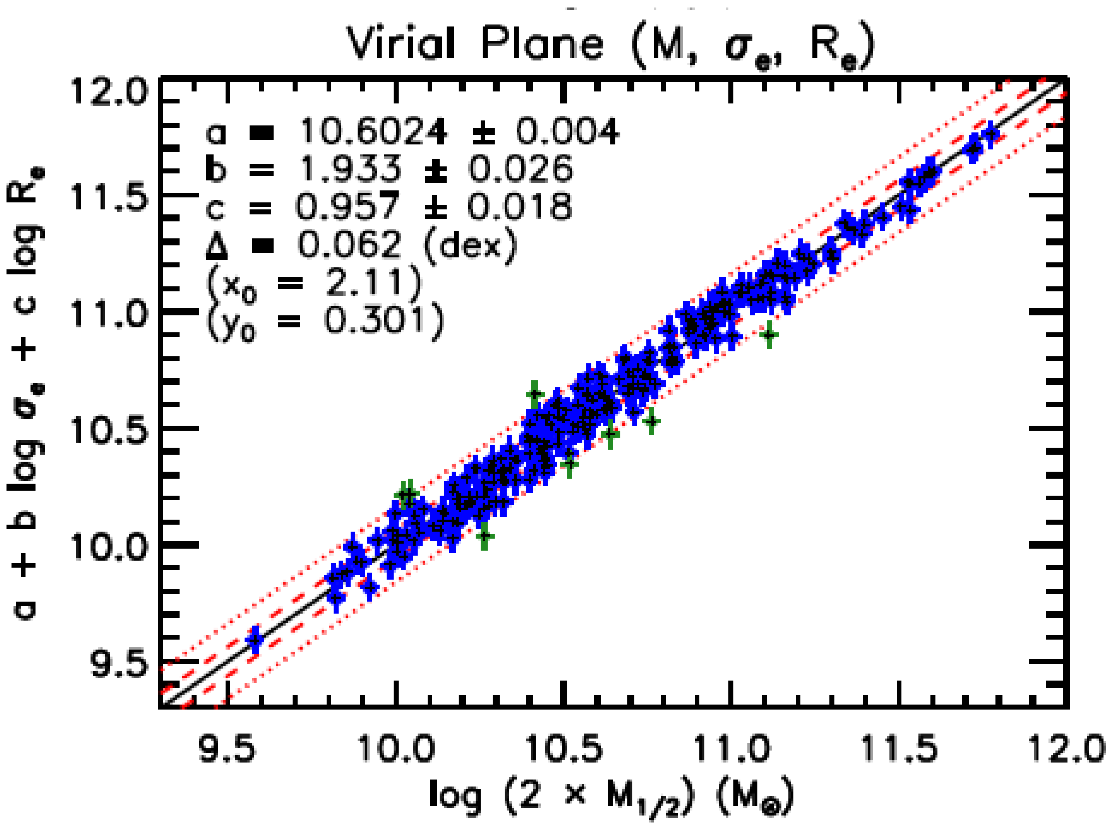
- Virial Plane,- replacing stellar luminosity with the total dynamical mass.
- Expect log L=a+blogσ+clog R_e

expect b=2, c=1 for virial theorm but find c~1 and b~1.4 (FP)

if take major part of the scatter in the FP is due to variations in the M/L

Thus the virial theorem is applicable,

2) that the derived mass enclosed within the half-light radius, r_h, is only weakly dependent on the distribution function of the tracer particles and the gravitational potential



Mass Determination

- If we cast the equation in terms of observables (MWB pg 579-580)
- only 'non-trivial' Jeans eq for a spherical system is
- $(1/\rho)d(\rho(v^2)/dr)+2\beta(r)v^2/r=-d\phi/dr$

$\beta(r)$ describes the anisotropy of the orbit

re-write this as $M(R)=-(\langle v_r^2\rangle r/G)[d\ln/d\ln r+d\ln v_r^2/d\ln r+2\beta]$

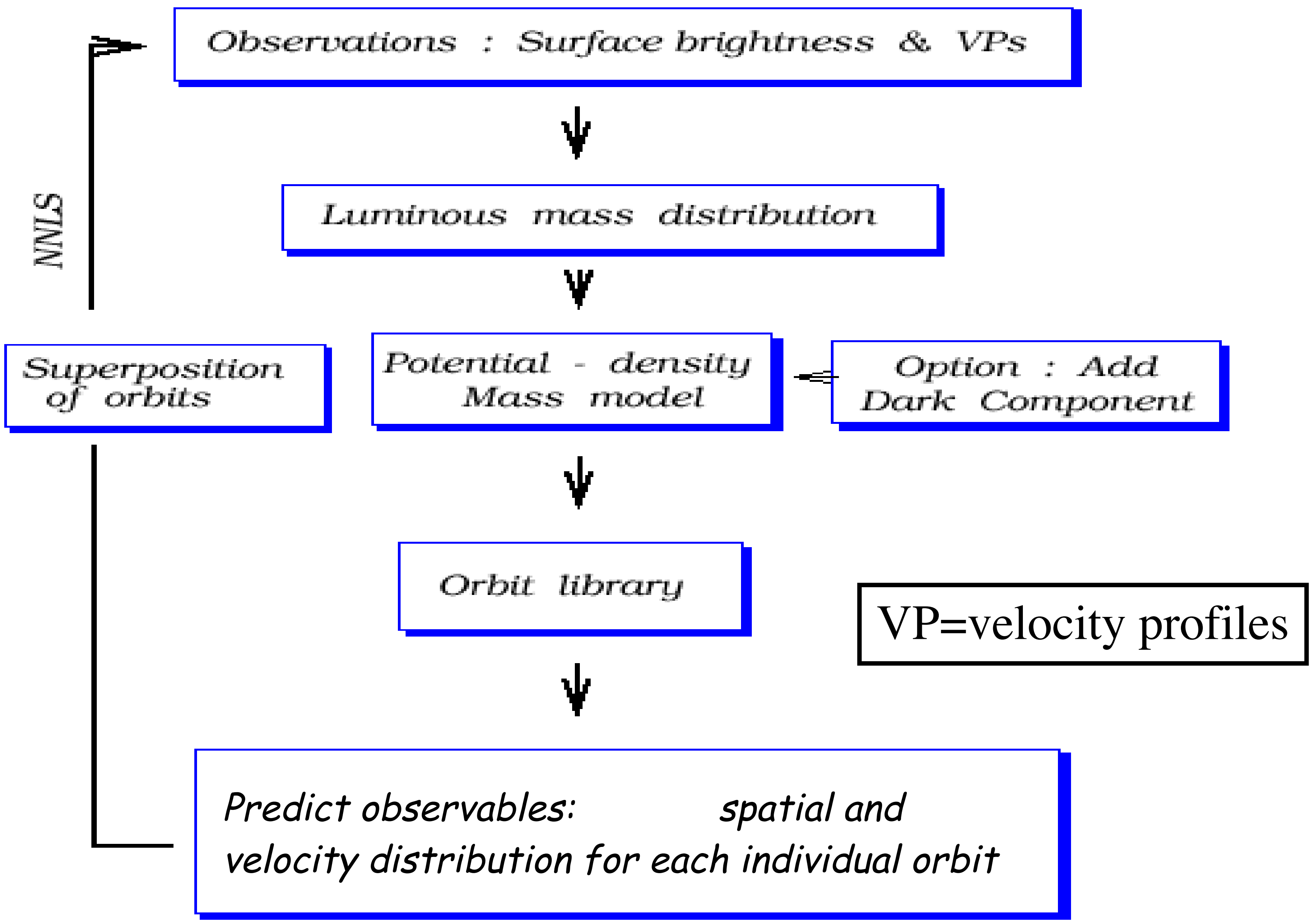
the projected velocity dispersion $\sigma^2_p(R)$

$\sigma^2_p(R)=2/I(R)\int(1-\beta R^2/r^2)n(v^2)rdr/sqrt(r^2-R^2)$- no unique solution since the observable $\sigma^2_p(R)$ depends on both v_r^2 and β

Schwarschild Orbit-Superposition Models

Degeneracies- many different orbit combinations can produce the same mass model

- The technique is due to Schwarzschild (1979)-see MWB pg 581 for details - requires very high quality data and lots of computational resources- but is now being done.


Observations : Surface brightness & VPs
Luminous mass distribution
Potential - density Mass model
Option : Add Dark Component
Superposition of orbits
NNLS
Orbit library
VP=velocity profiles
Predict observables: spatial and velocity distribution for each individual orbit

“Orbit-based” Models

Schwarzschild Models (1978)- see

http://www.astro.virginia.edu/class/whittle/astr553/Topic08/Lecture_8.html

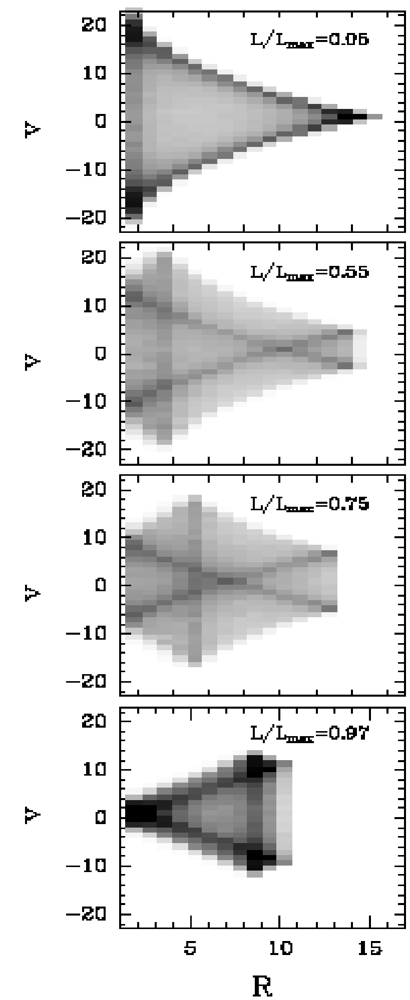
Describing Collisionless Systems

- What would the galaxy look like, if all stars were on the same orbit?
  - pick a potential F
  - Specify an orbit by its “isolating integrals of motion”,An "integral of motion" is a function

    I (r, v) which is constant along a star's orbit
  - e.g. Energy (in a static potential), J (total angular momentum in spherical potential) or J_z (z component of AM in a axisymmetric static potential)
  - I (r, v) is a solution of the steady state collisionless Boltzman eq
  - Integrate orbit to calculate the
    - time-averaged
    - projected

  properties of this orbit

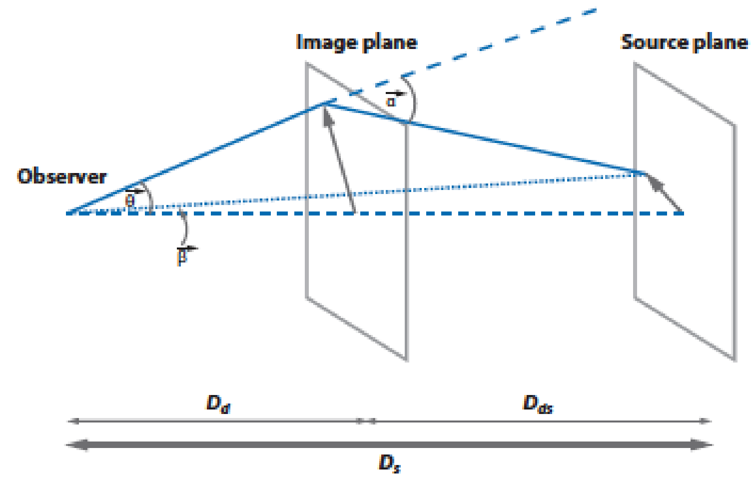
  (NB: time average in the calculation is identified with ensemble average in the galaxy at on instant)
  - Sample “orbit space” and repeat



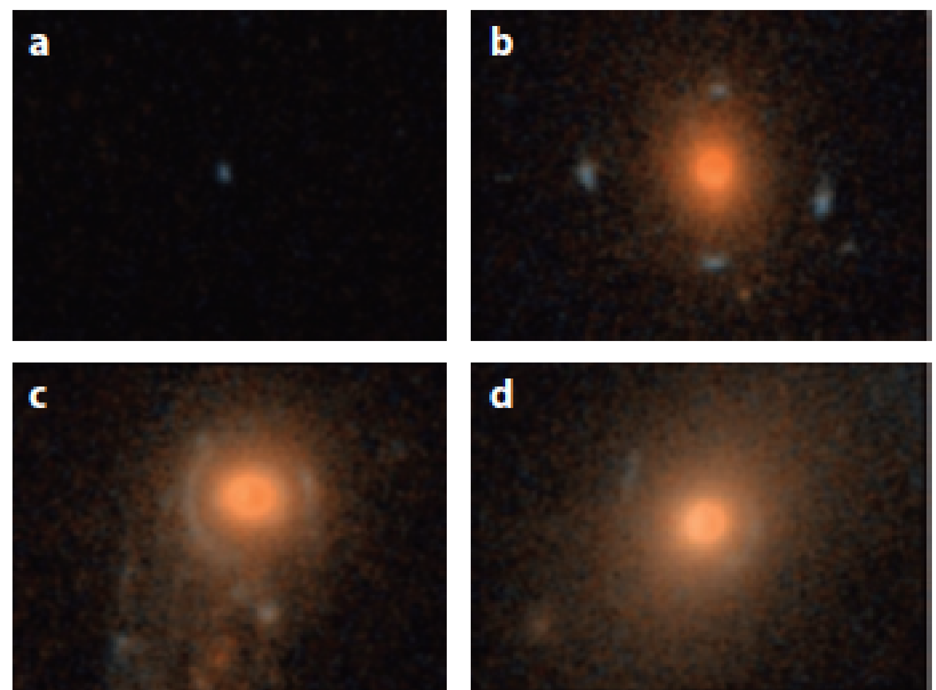
from Rix et al 1997

Lensing

- Strong lensing observables — such as relative positions, flux ratios, and time delays between multiple images — depend on the gravitational potential of the foreground galaxy (lens or deflector) and its derivatives



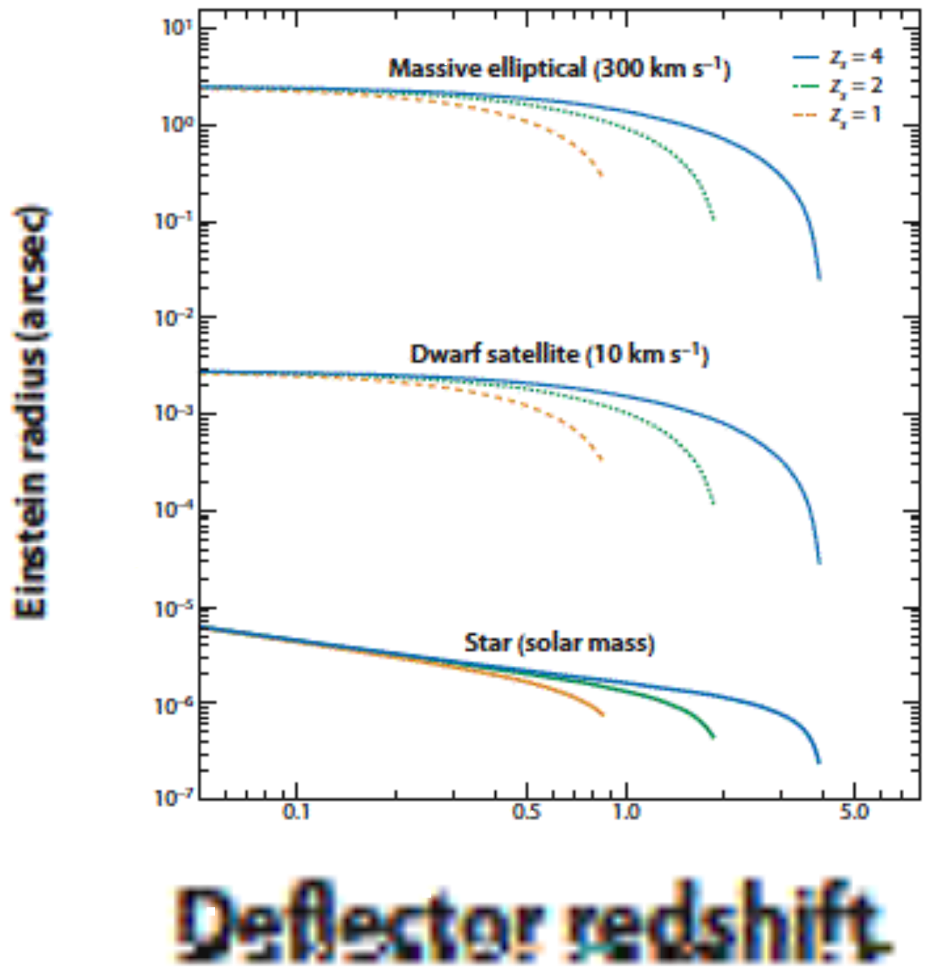
- dynamical models provide masses enclosed within a *spherical* radius, while strong lensing measures the mass inside a *cylinder* with axis parallel to the line-of-sight
- Einstein radius $\theta_e=4\pi(\sigma_{sis}/c)^2D_{dt}/D_s$
- where, σ_{sis} is the velocity dispersion of a simple isothermal potential D_{dt} is the distance from lens to source and D_s is the distance from observer to source



3 most common lensed images quad, Einstein ring, a double

Why Giant Ellipticals as Lenses

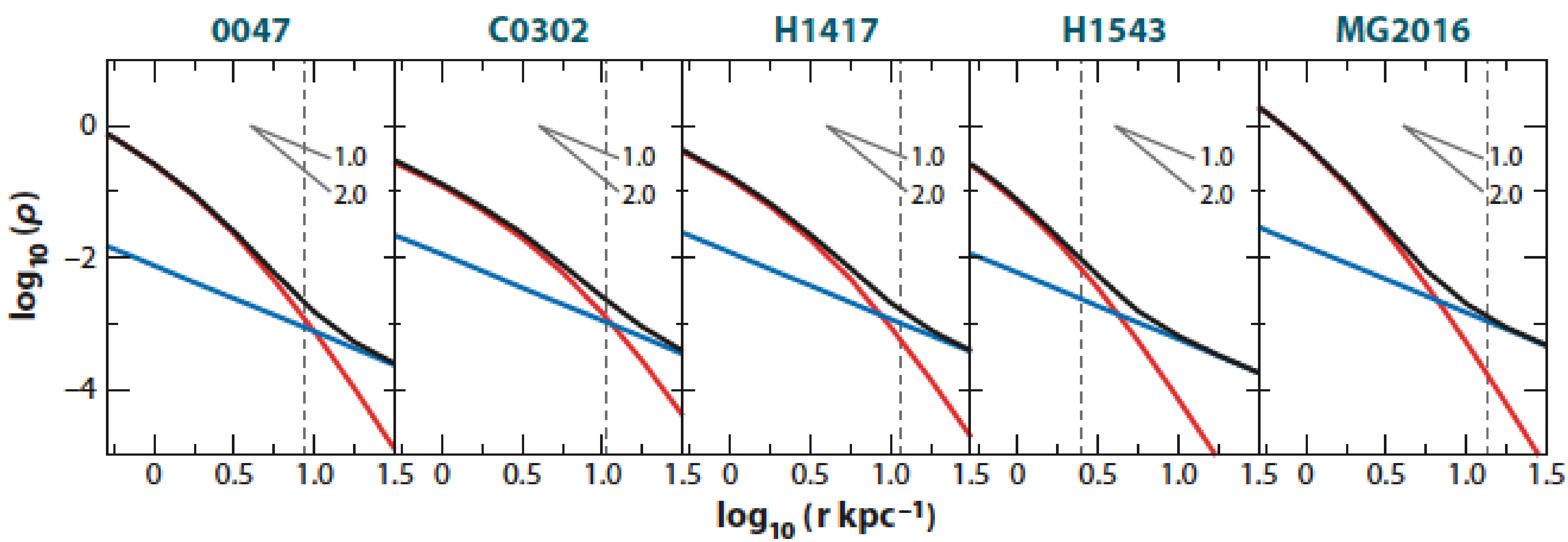
- To first order strong lensing is only sensitive to the mass enclosed by the *Einstein radius*
- Ellipticals Einstein radii are ~2" over a wide range of redshifts - but only 1/1000 galaxies are strong lenses
- cross section (Einstein radius^2) goes as σ^4. Ellipticals tend to have higher σ



Treu 2010

Mass Profiles From Lensing + Photometry

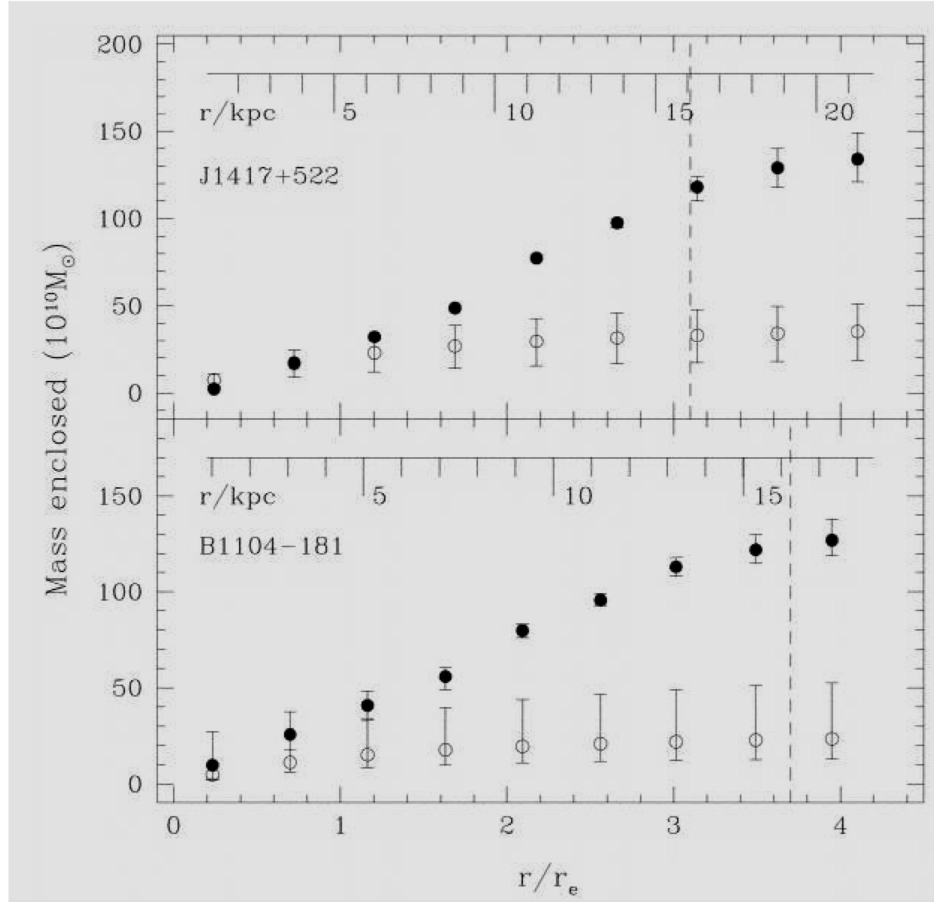
- Blue is mass density of dark matter, red that of stars for 4 galaxies (Treu 2010) as a function of radius (vertical line is Einstein radius)
- Dark dominates in all of these at large radii
- While neither stars nor DM have a power law distribution in density the sum does-similar to the disk-halo conspiracy responsible for the flat rotation curves of spiral galaxies ; this is the "bulge-halo conspiracy."
- Notice that in *inner regions are dominated by stellar mass*



blue is dark matter, red is stars, black is total

Degeneracies

- degeneracies inherent in interpreting projected data in terms of a three-dimensional mass distribution for pressure-supported systems.
- Chief among these degeneracies is that between the total mass-density profile and the anisotropy of the pressure tensor
- The dark matter fraction increase as one goes to large scales and with total mass
- Density profile is almost isothermal
- $d \log \rho_{tot} / d \log r \sim r^{-2}$ which corresponds to a flat circular velocity profile



black points total mass, open points stellar mass for two lensed galaxies

Ferreras , Saha , and . Williams 2005