Elliptical Galaxies So Far

- Visual Impression: smooth, roundish- *deceptively* simple appearing- collisionless systems
- Stars are very old
- Strong correlations of many properties: size, surface brightness, metallicity, velocity dispersion, color, luminosity
  - more massive systems tend to be 'older'
- 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) ; n~4 for massive systems.
- Most massive ellipticals ($M_{star}>10^{10}M_\odot$) lie on the **'fundamental plane'** which includes **velocity dispersion, size , luminosity surface brightness** (and some other properties like metallicity)

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

Final Exam and Project

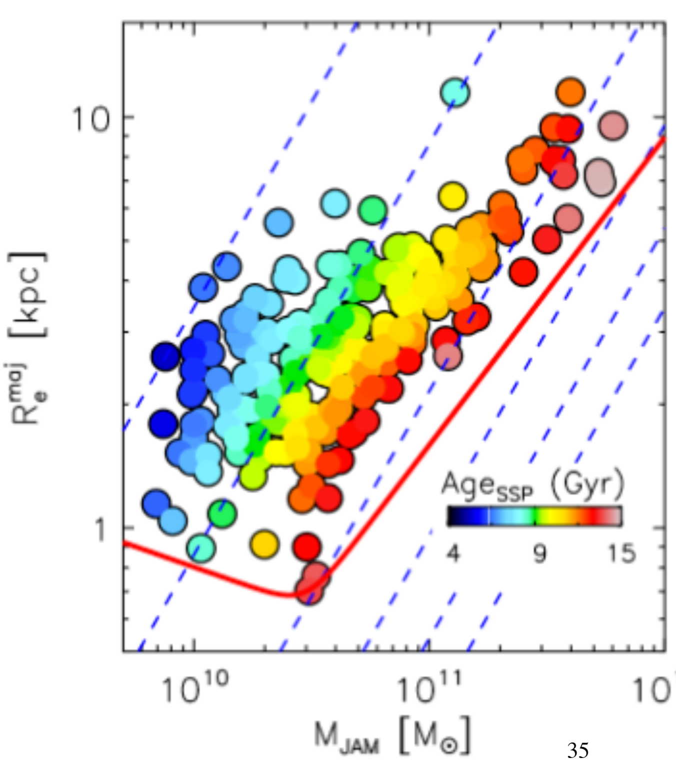
Final

Friday May 19 10:30 am - 12:30 pm this room

deadline for project May 2

Age is Also Related to Mass and Size

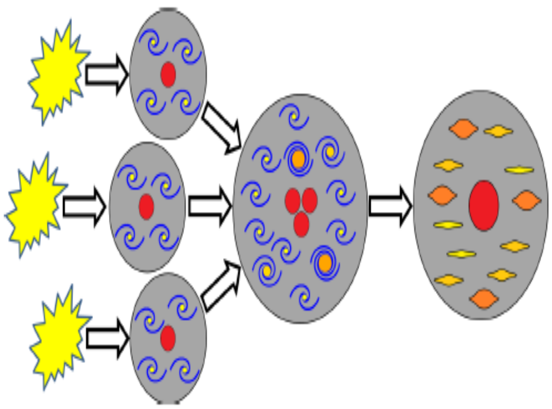
- More massive galaxies are, on average older (McDermid et al 2015)
- This is 'backward' from simple ideas of hierarchical galaxies formation where small things form first!!

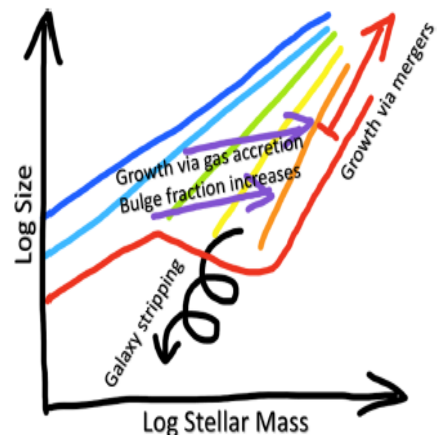


General Idea of Growth-

- At high redshift gas clouds collapse, stars form, galaxies start growing rapidly
- As time goes on this process slowly stops and the merger of smaller objects into the proto-E galaxy dominates growth

Michele Cappellari





A lot more detail

- van Dokkum et al 2015 E galaxy formation has followed two main simple evolutionary tracks

(i) Growth dominated by gas accretion. The originally gas rich

and star forming galaxies become denser, increasing their velocity dispersion , until they reach a threshold at which star formation is quenched.

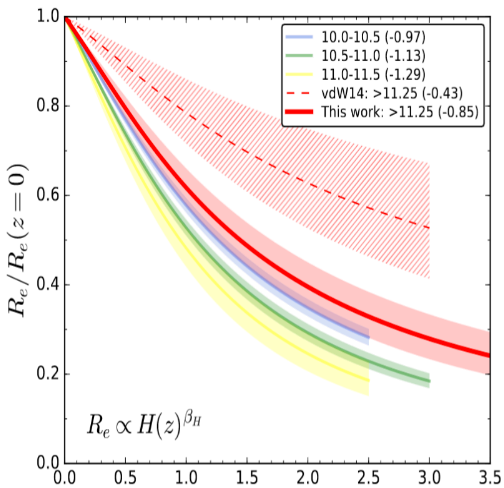
(ii) A steeper track dominated by (mainly dry) mergers,

where their size increase proportionally to their mass.

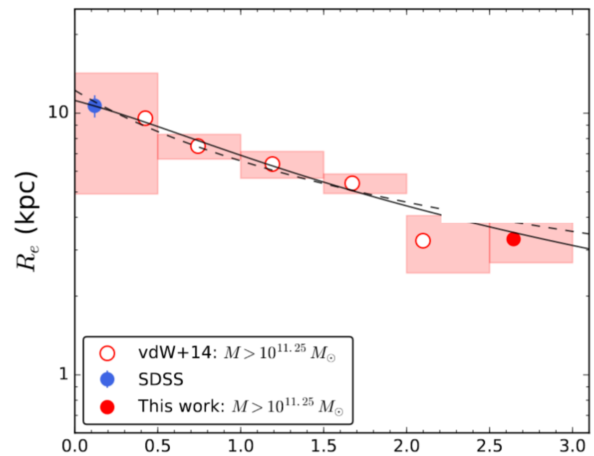
Although the detailed mechanism is still actively debated, the need for 'quenching' (a sudden stop in the growth of galaxies from star formation) is needed (feedback)

Size Growth of Massive Elliptical

- Half light radii for $M \geq 10^{11.25} M_{\odot}$ vs redshift (Patel et al 2017)
- Elliptical Galaxies grow in size over cosmic time
- Rate at which they grow depends on mass- more massive ones at early times grow slower



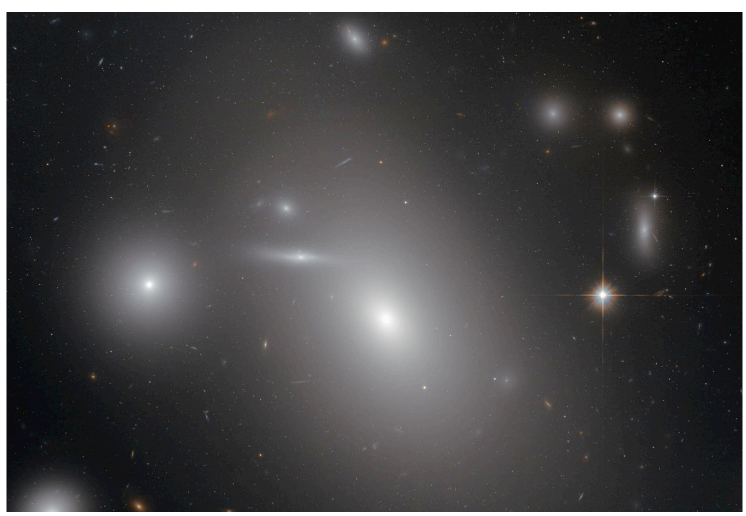
Z

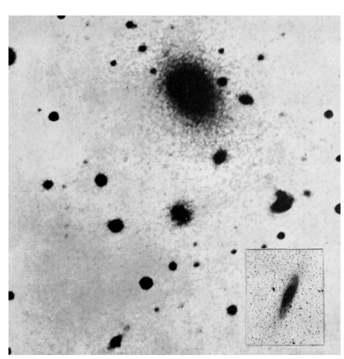


Z

Special Objects- The most massive systems

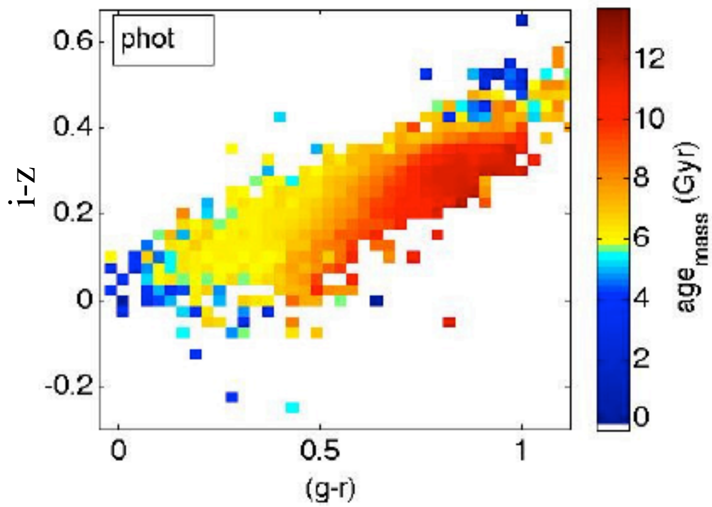
- 'cD' (central dominant) galaxies lie only at the centers of groups and clusters- not all brightest clusters- not all brightest cluster galaxies (BCGs) are cDs.
- Their surface brightness profiles are very extended and they often have very rich populations of globular clusters. Quite spheroidal shape.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





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.

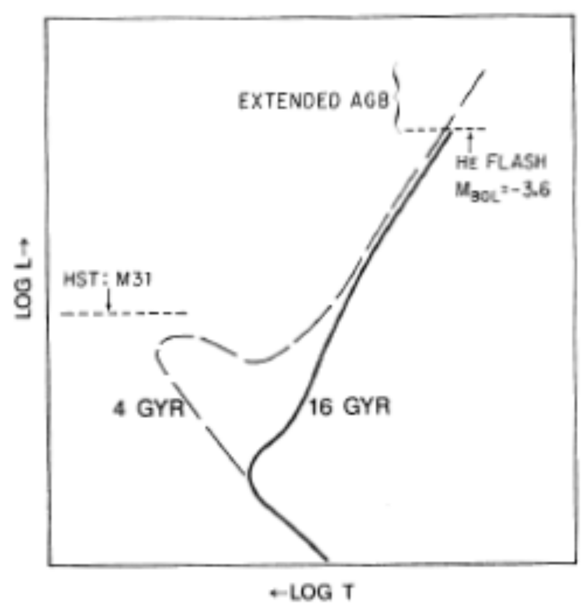


Color-color plot
Graves et al 2011

Objects with a certain range of colors can be mapped to the ages of the systems

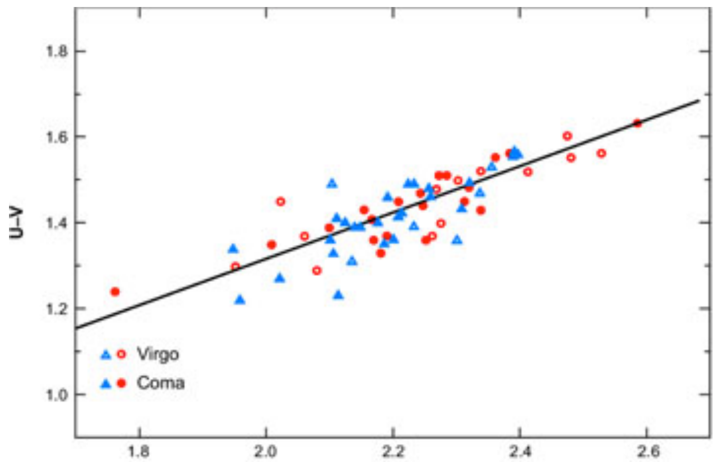
Problem in Getting Ages

- 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 only a small difference between 4 and 16Gyr aged populations



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 almost unchanged

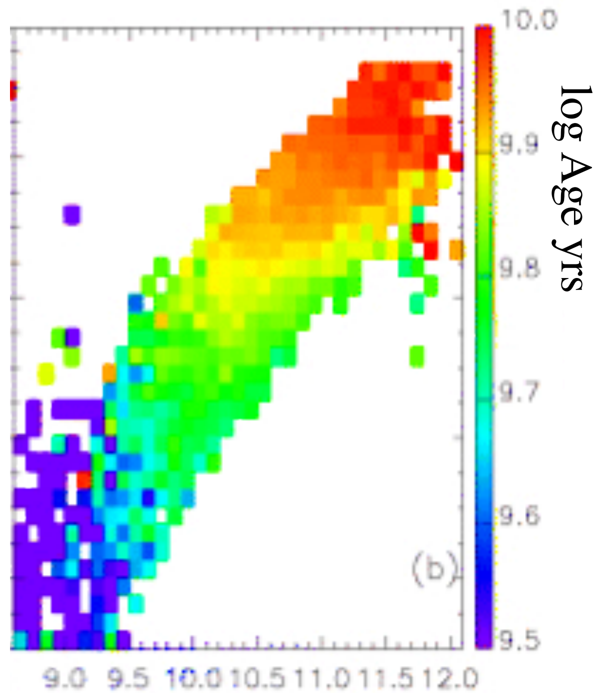


log σ

Bower, Lucy, Ellis 1991

More Massive Galaxies are Older

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

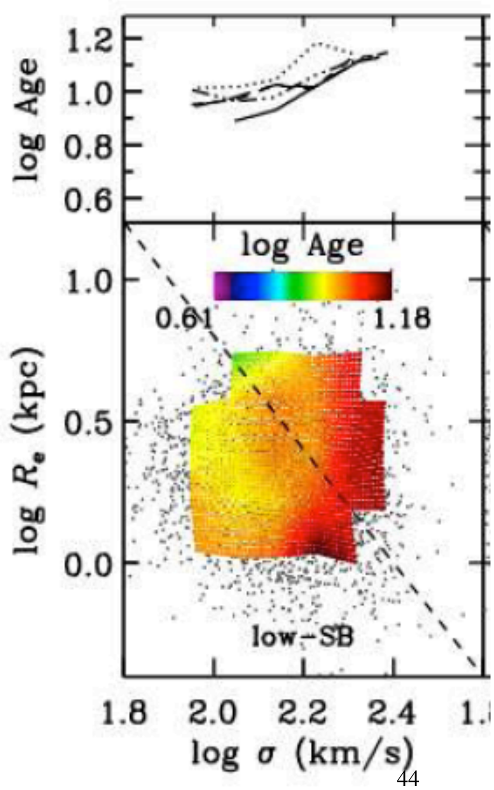


log $M/M_{\odot}$

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, indicating that stellar population age is independent of R_e (scale length in Sersic fit) at fixed σ (stellar velocity dispersion.

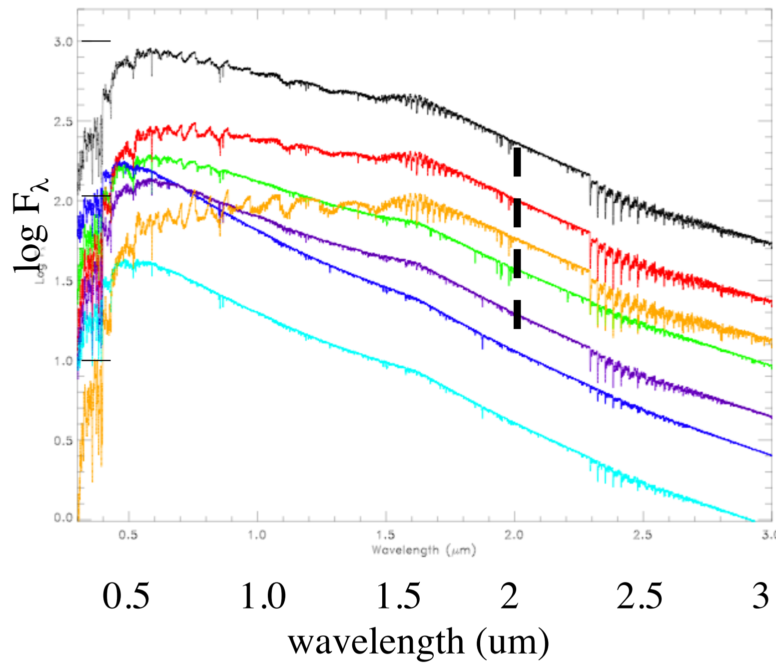


Optical Spectra

- 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 similar optical broad-band colors, 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

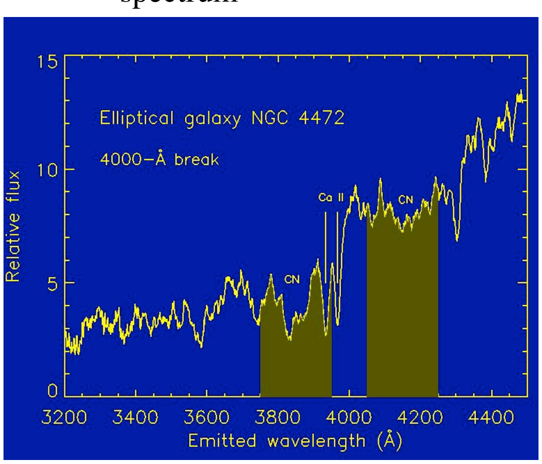
Synthetic Spectum of 16Gyr SSP- Kroupa IMF

- 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 in optical

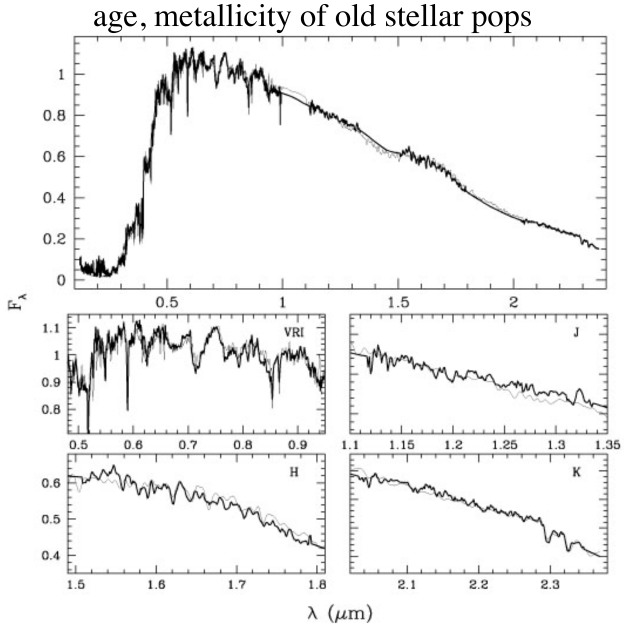


Spectrum of Ellipticals

- 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

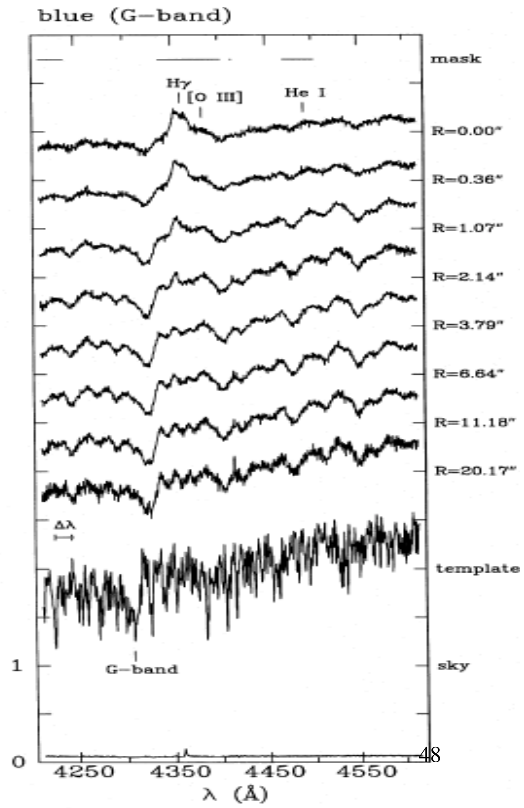


see GuyWorthy's web page http://astro.wsu.edu/worthey/dial/dial_a_model.html

Analysis of Spectral Data

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

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



48

Spectra

- With sufficient cleverness one can stack the spectra obtained from the SDSS based on photometric data (Conroy et al 2013) and thus overcome the difficulties of low amplitude differences expected for age/metallicity indicators.

2 CONROY, GRAVES & VAN DOKKUM

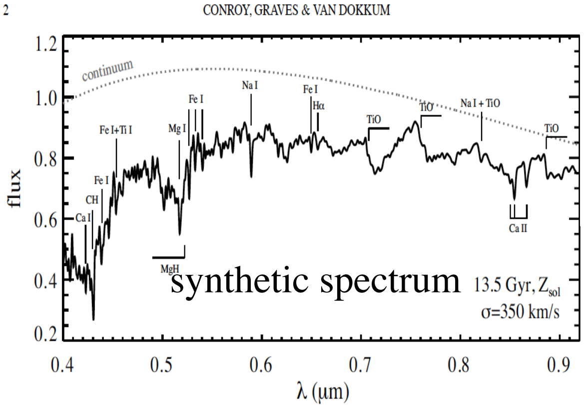


Figure 1. Model spectrum for an age of 13 Gyr and solar metallicity. The spectrum has been smoothed with a velocity dispersion of $\sigma = 350\ \mathrm{km\,s^{-1}}$, equal to the smoothing applied to the early-type galaxy data analyzed in this paper. Strong features are labeled. Also included is the 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.

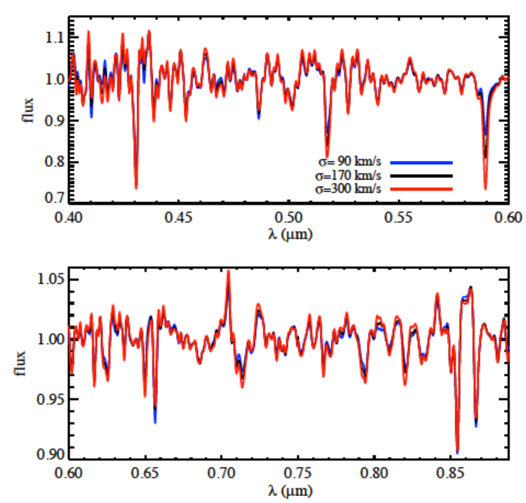


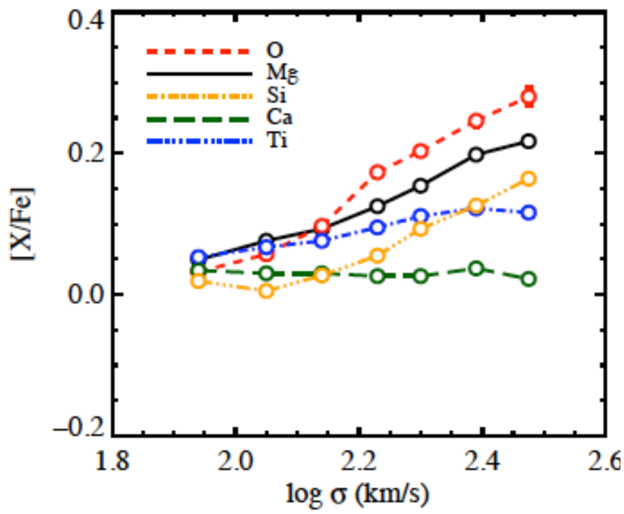
Figure 7. Continuum-normalized stacked spectra of SDSS early-type galaxies in three velocity dispersion bins.

stacked data in 3 velocity dispersion bins (3 colors) - see incredibly subtle differences in spectra

49

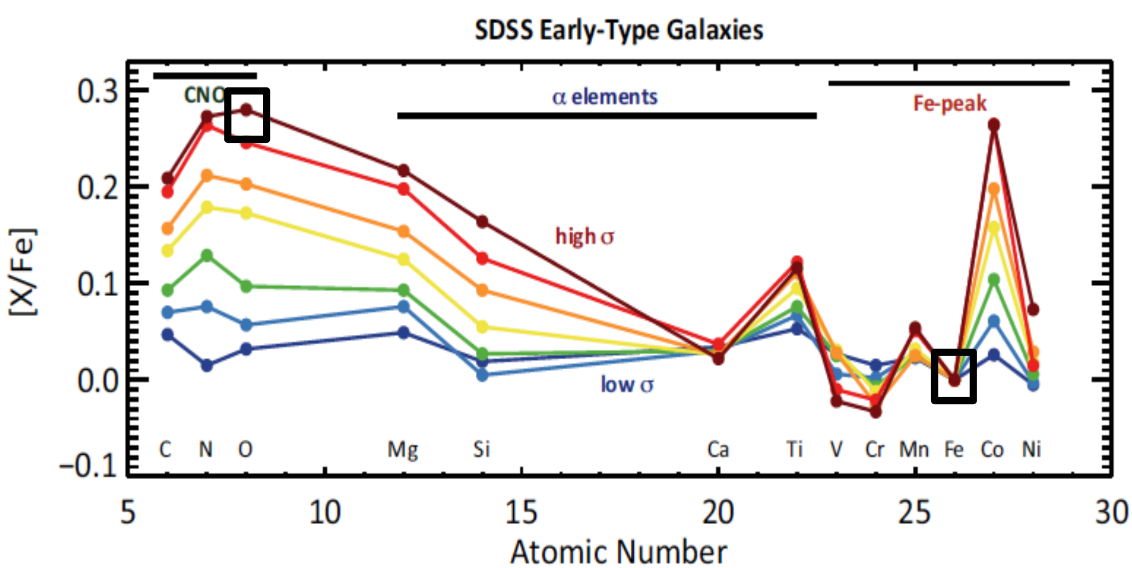
Metallicity

- Massive early-type galaxies are enhanced in the α elements (e.g. O, 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) (e.g. how long it takes for Ia's to explode compared to when the stars form)
  - the preferential loss of some metals via winds



Conroy et al 2013

Patterns from Spectroscopy



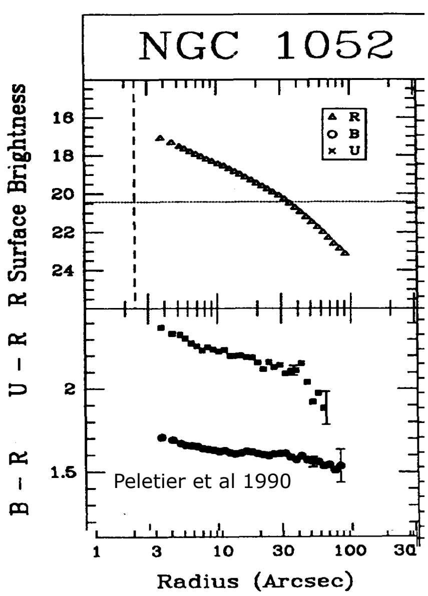
Conroy et al 2013

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)
- Detailed analysis (Graves et al 2010) shows that this is due to **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 and/or age gradients-e.g redder toward their centers. These gradients are fairly subtle; a factor of 10 decrease in radius typically produces a change of 0.25 mag in (U-R)



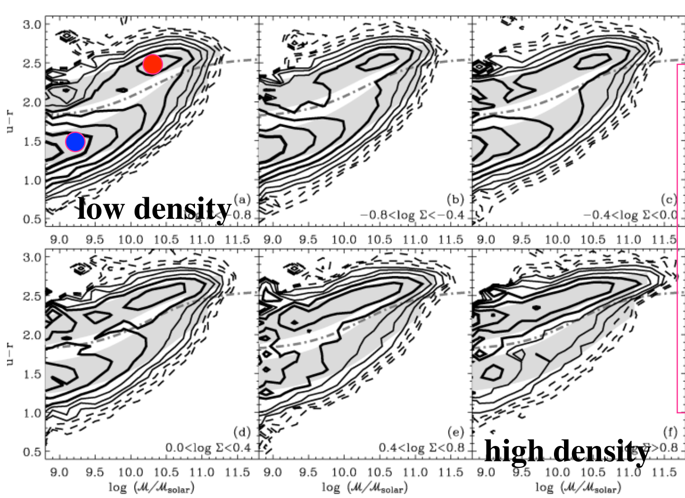
Because of the color-age degeneracy its not clear what causes the color gradients <u>without spectra</u>

Summary of Abundance Data

- All early-type galaxies obey a metallicity–luminosity relation
  - less massive galaxies are less metal rich
  - 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 called cosmic downsizing; 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

  - BUT if ellipticals are primarily formed by mergers, made in regions where mergers are more frequent, but galaxies are not moving too fast (otherwise not merge)

Faber-Jackson

- Roughly, $L \sim \sigma^4$
- – More luminous galaxies have deeper potentials
- follows from the Virial Theorem (see derivation of Tully- Fisher, but now use σ instead of $v_{circular}$)
- Dimensional analysis $\sigma^2 \propto GM/R$ and thus $R \propto \sigma^2 I^{-1} (M/L)^{-1}$
- compared to actual fit of $R_e \propto \sigma^{1.4} I^{0.9-}$ these are consistent if $(M/L) \propto M^{0.2}$
- More detailed analysis shows that the the intrinsic scatter and tilt of this relation is driven by stellar population variations, including the stellar initial mass function,

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

The F-J 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 with Mas

Fundamental plane : measurements of σ and surface brightness profile correlated with (M/L)

Faber-Jackson

- Roughly, $L \sim \sigma^4$
- – More luminous galaxies have deeper potentials
- follows from the Virial Theorem (see derivation of Tully- Fisher, but now use σ instead of $v_{circular}$)
- Dimensional analysis $\sigma^2 \propto GM/R$ and thus $R \propto \sigma^2 I^{-1} (M/L)^{-1}$
- compared to actual fit of $R_e \propto \sigma^{1.4} I^{0.9-}$ these are consistent if $(M/L) \propto M^{0.2}$
- More detailed analysis shows that the the intrinsic scatter and tilt of this relation is driven by stellar population variations, including the stellar initial mass function,

Fundamental plane

6 observables are all correlated via **the fundamental plane**
Luminosity, Effective radius, 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 with Mass

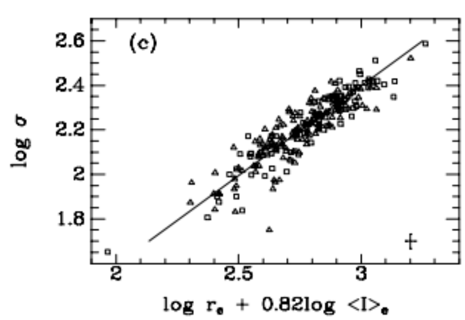
\

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-relates structural/dynamical of Ellipticals to their stellar content.

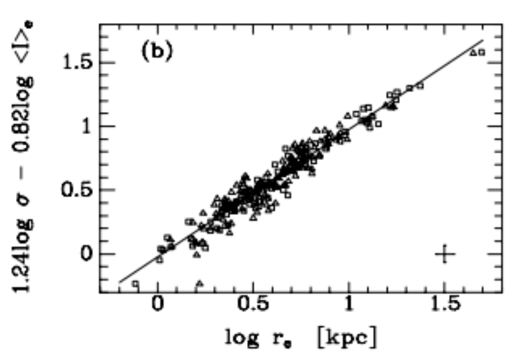
Three key observables of elliptical galaxies, effective radius R_e, the central velocity dispersion σ, luminosity L (or equivalently the effective surface brightness $I_e = L/2\pi R_e^2$)



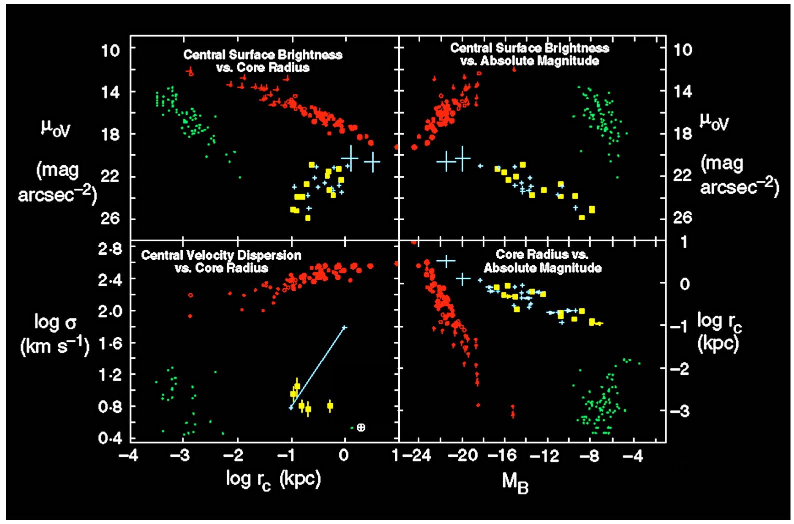
Elliptical galaxies are not randomly distributed within the 3D space (R_e, σ, I_e), but lie in a plane

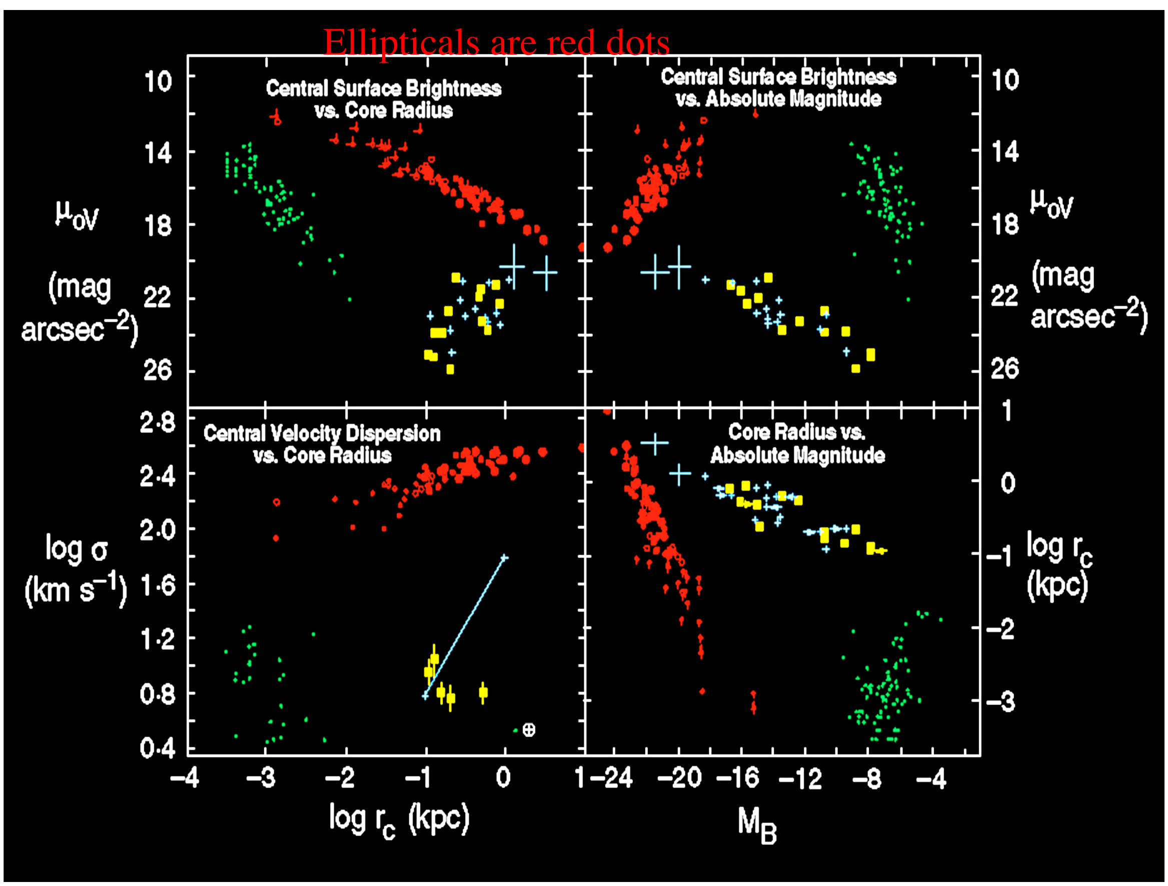
The existence of the FP implies that ellipticals

- 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.



- 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 $R_e \sim \sigma^a I_e^b$
- a projection over the (σ,$L = 2\pi I_e R^2_e$) plane generates the Faber-Jackson relation (Faber & Jackson 1976).



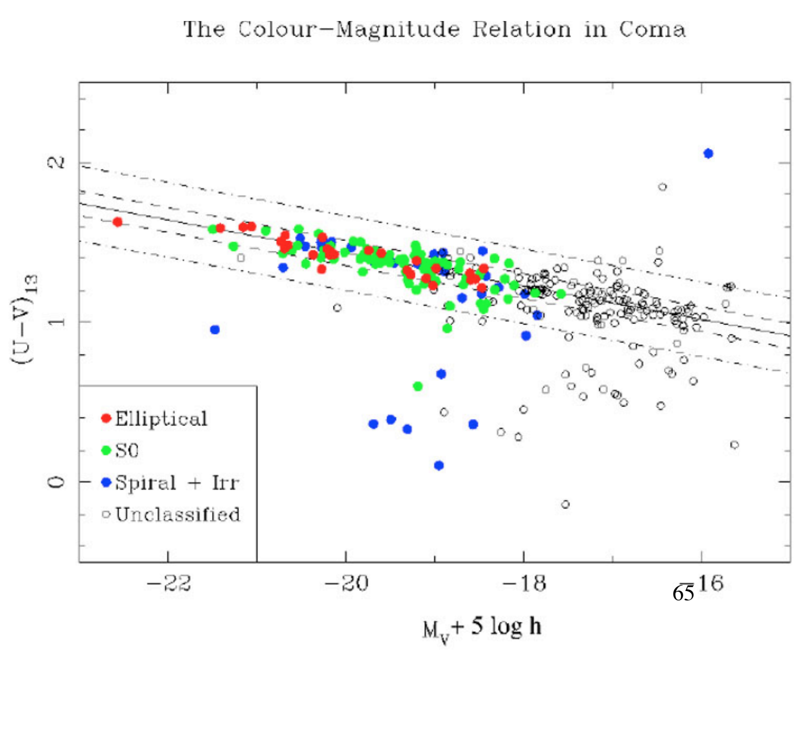


What Does Fundamental Plane Tell US

- 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 $R_e = \sigma^2/\Sigma_e$, (Σ_e 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.

Color Magnitude relation

- Colors of elliptical galaxies strongly connected to their luminosity and have only a narrow range



Scaling Relations

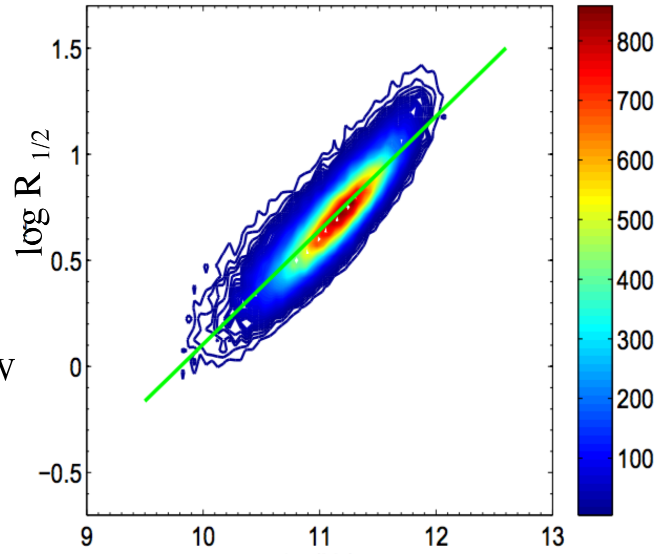
- There is a very strong relation between the **size and stellar mass** of normal elliptical galaxies with

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

Notice the very high density of objects in the core of the relation (Shen et al 2009)

A test of formation theory: (MBW pg596)

situation is a bit complex see discussion in MBW 597-600

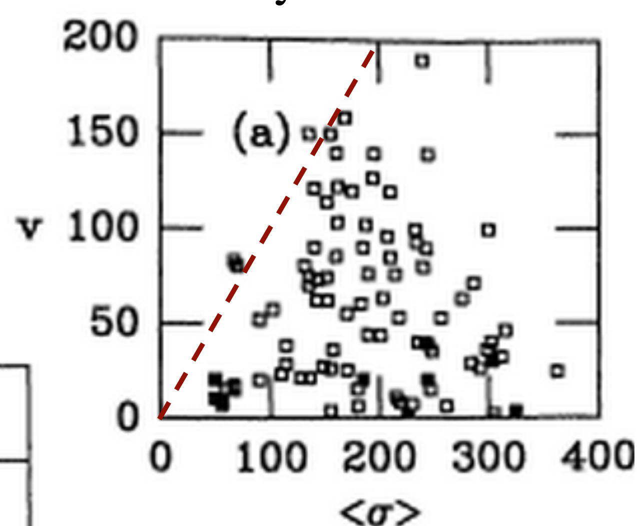


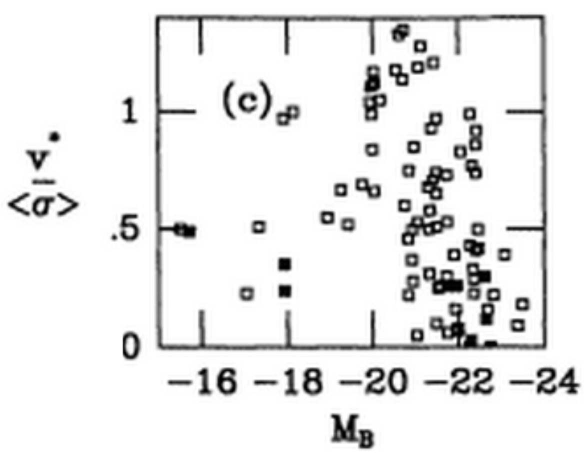
log $M_{stellar}$

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

Summary So Far

- Fundamental plane connects luminosity, scale length, surface brightness, stellar dynamics. age 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