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 this room

- This is the date on the University schedule: we **can** change it if the class desires- Julie Rose sent out a doodle poll- do we have a conclusion yet

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

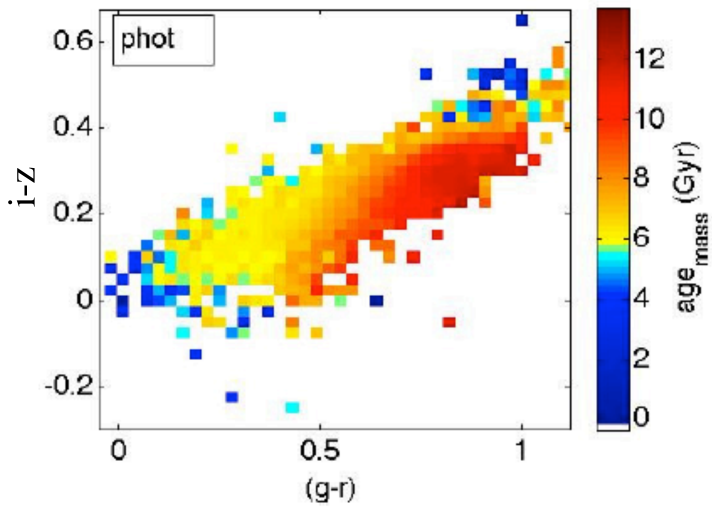
smaller Sersic indices

Special Objects-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.

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.

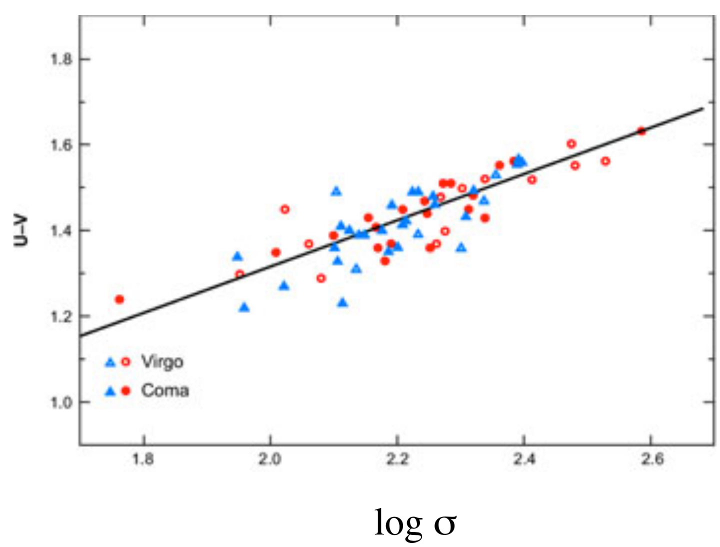


Color-color plot
Graves et al 2011

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

Color - Velocity Dispersion

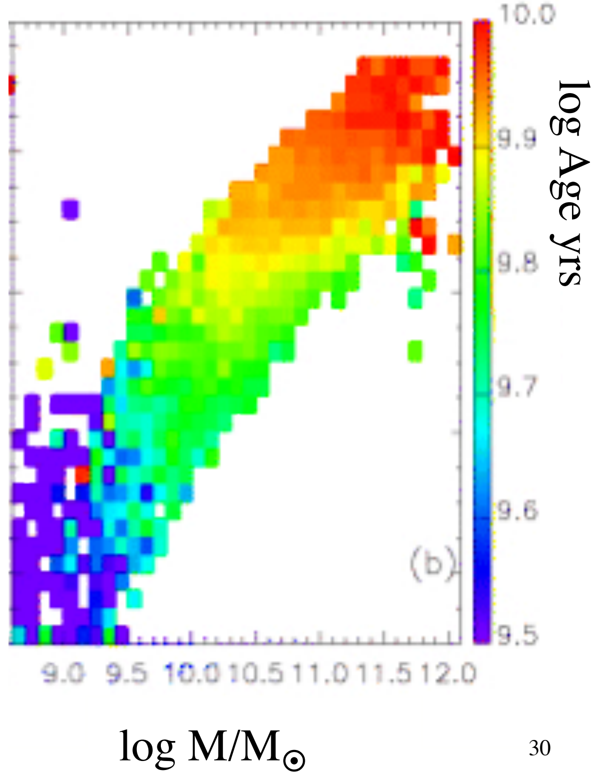
- Strong relation of color and velocity dispersion- a projection of the *fundamental plane* where velocity, size, luminosity strongly correlated
- the color- velocity dispersion relation strongly constrains 'dry' mergers since merging without star formation increases mass (related to σ via the virial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



Bower, Lucy, Ellis 1991

More Massive Galaxies are Older

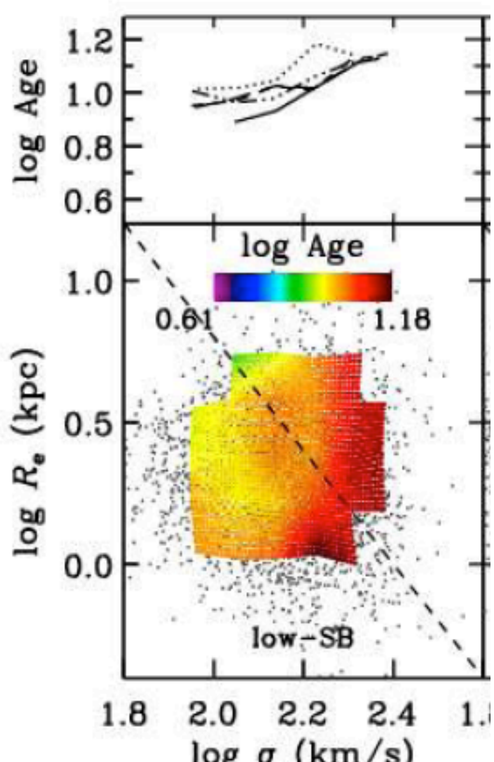
- small but systematic trends for more massive and luminous galaxies tend to be older



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*

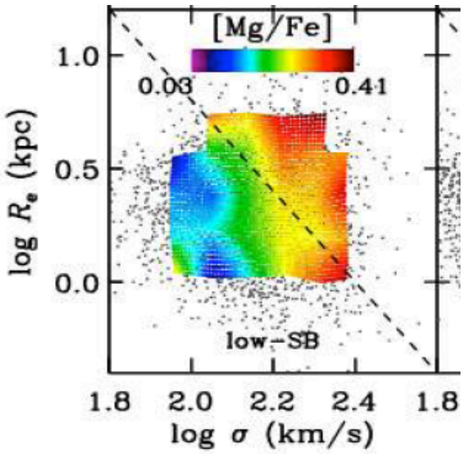
Strong connection of chemical composition structural parameters, mass, age...
Strong clues to how stars/ galaxy form...

- 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.

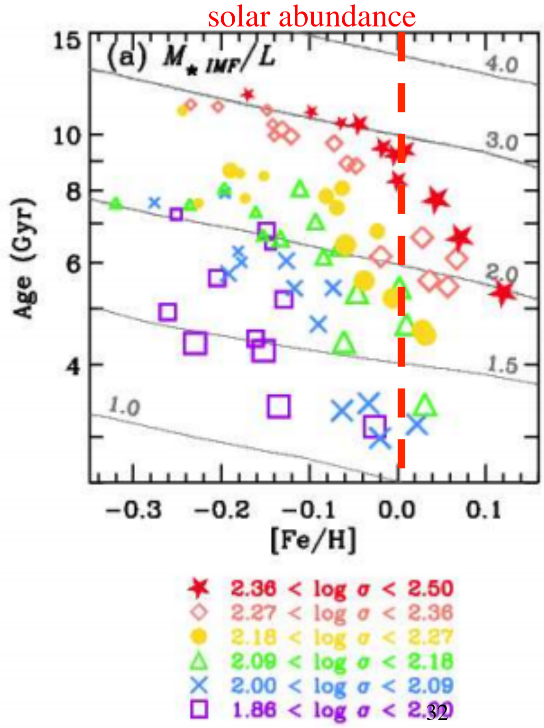


Metallicity

- 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

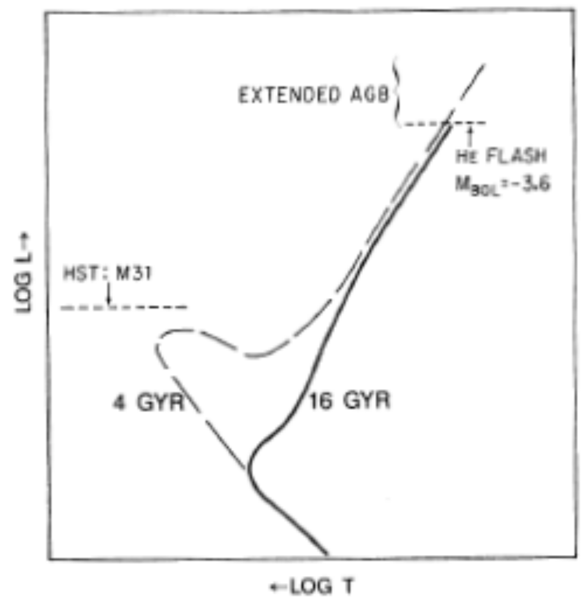


Optical Spectra

- 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

Problem in Getting Ages

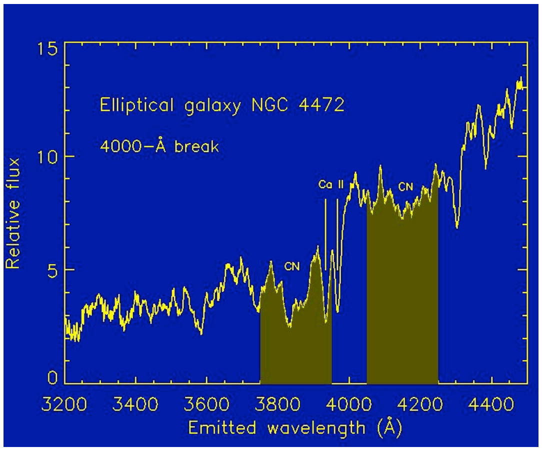
- The problem is that most of the stellar light is from giants but most of the mass is on the Main Sequence
- On the giant branch there is not much difference between 4 and 16Gyr aged populations

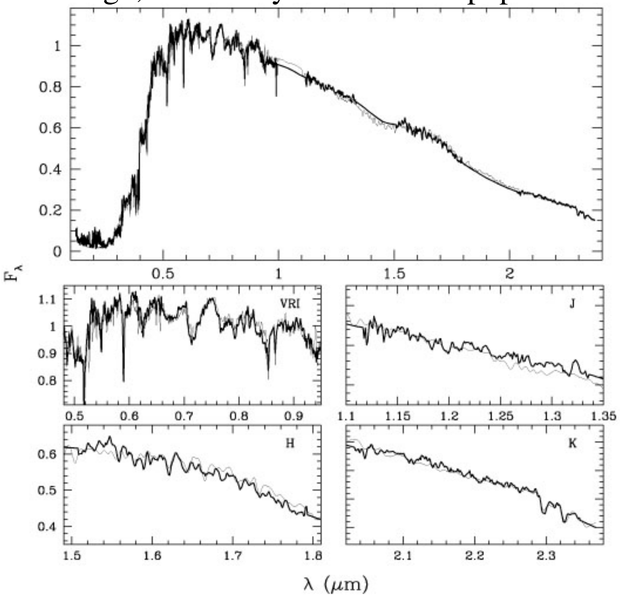


Spectrum of Ellipticals

- 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

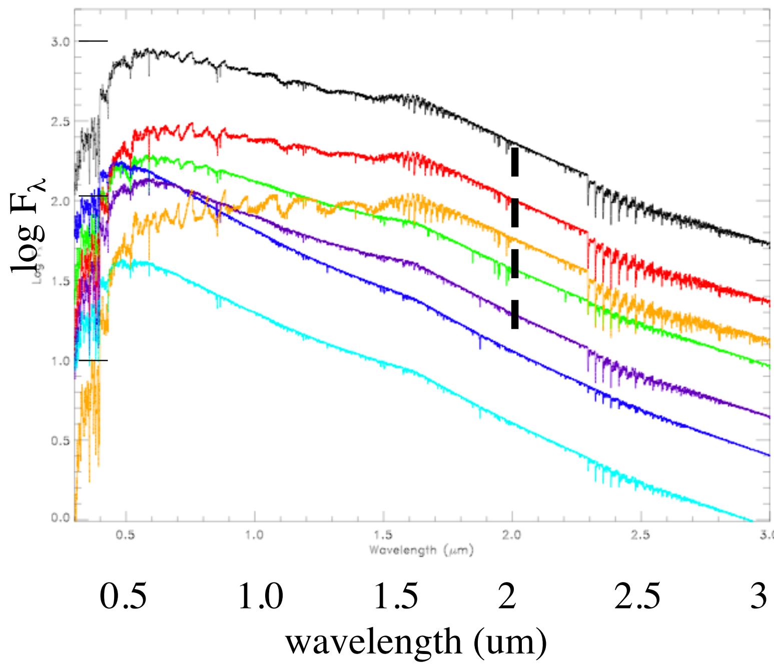




see GuyWorthy's web page http://astro.wsu.edu/worthey/dial/dial_a_model.html

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

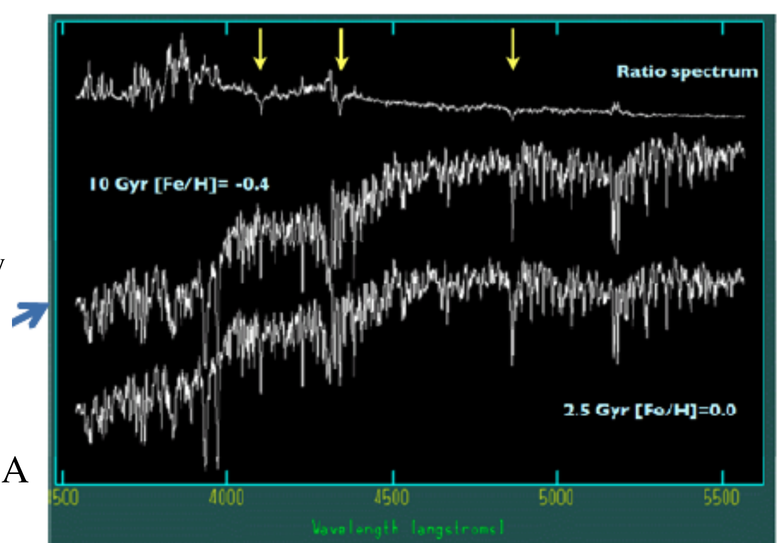


Age Metallicity Degeneracy

- 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,

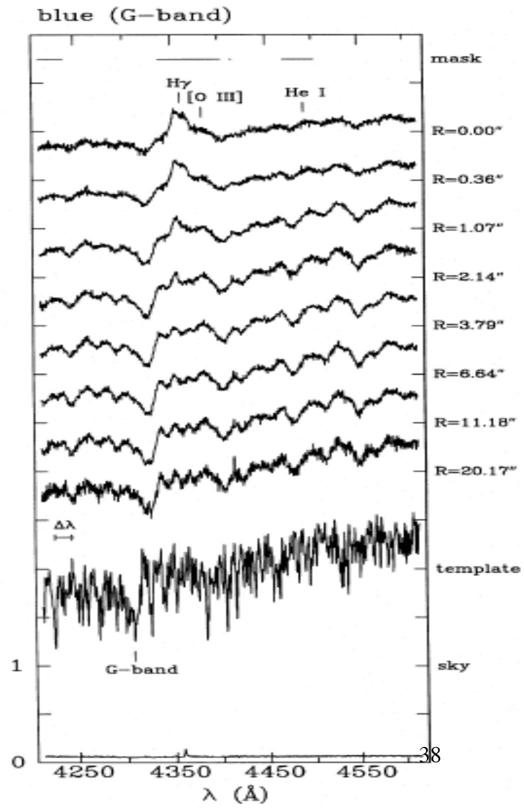
theoretical spectra of stellar pops 3500-5500A
10Gyr [Fe/H]=-0.4
2.5Gyr [Fe/H/=0.0



Vazdekis et al. (2007) models from MILES library

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

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.

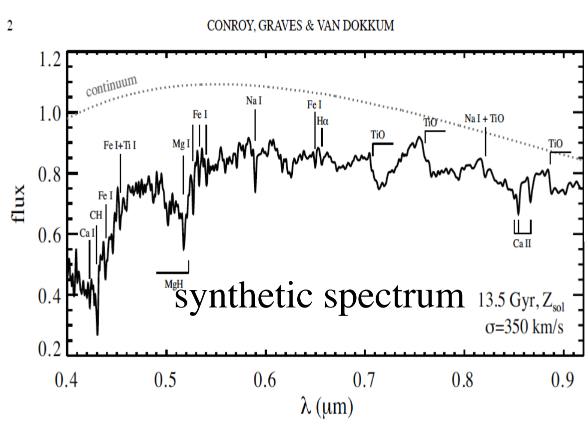


Figure 1. Model spectrum for an age of 13 Gyr and solar metallicity. The spectrum has been smoothed with a velocity dispersion of $\sigma = 350\ \mathrm{km\,s^{-1}}$, equal to the smoothing applied to the early-type galaxy data analyzed in this paper. Strong features are labeled. Also included is the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

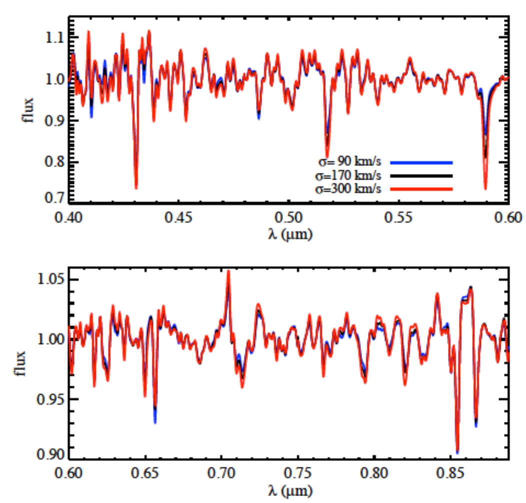
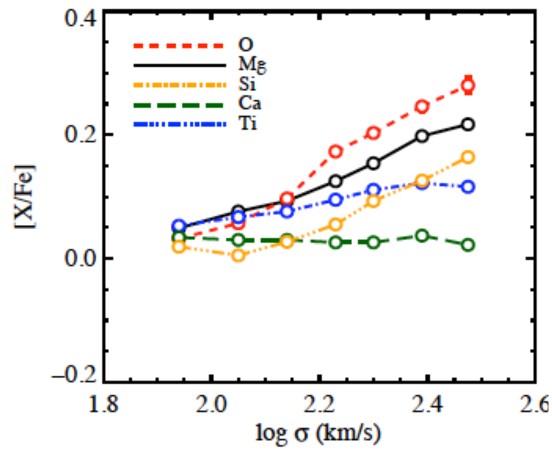


Figure 7. Continuum-normalized stacked spectra of SDSS early-type galaxies in three velocity dispersion bins.

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

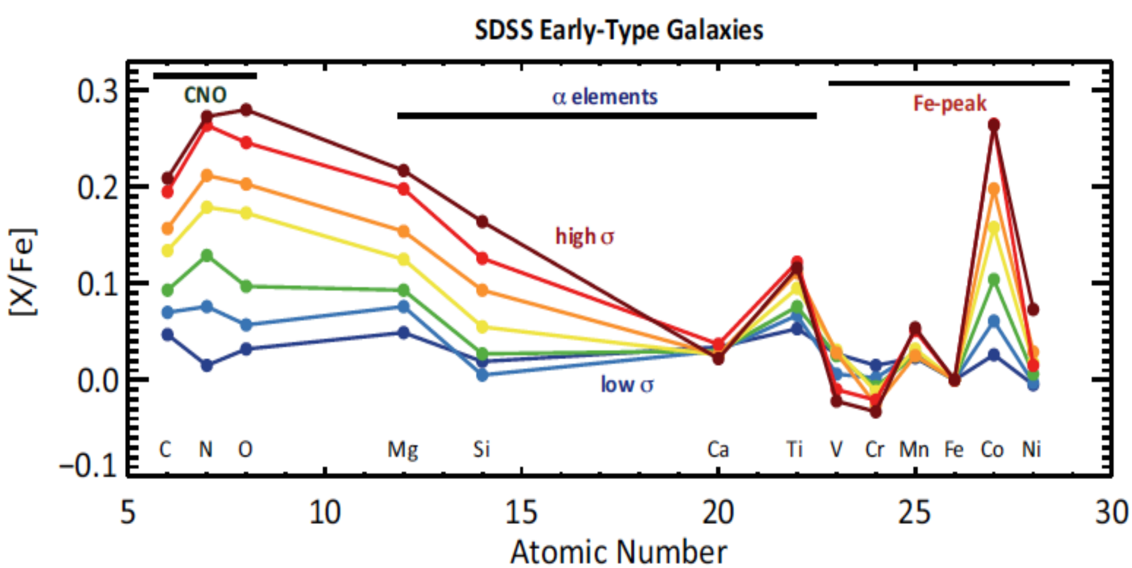
Metallicity

- 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

Patterns from Spectroscopy



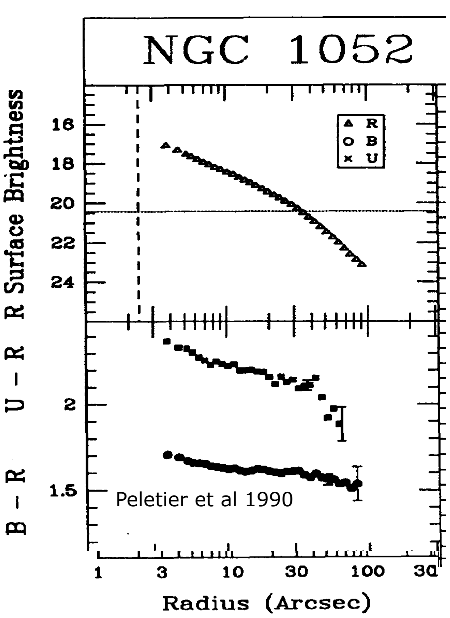
Conroy et al 2013

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

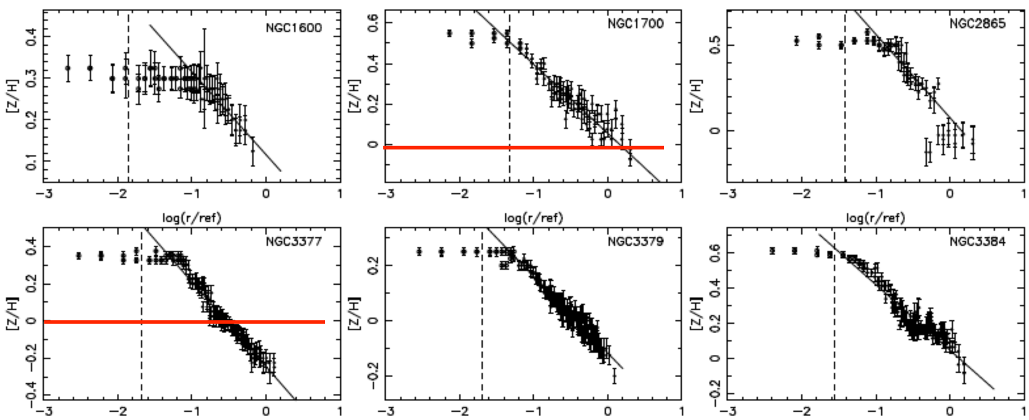
- Almost all galaxies become bluer outward- mostly due to decreasing metallicity



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

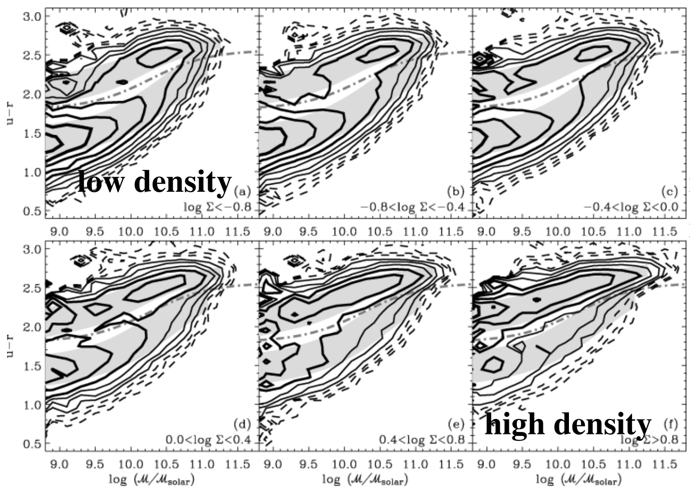
Summary of Abundance Data

- 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 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

  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).

Faber-Jackson

- Roughly, L ~ σ^4
- – More luminous galaxies have deeper potentials
- follows from the Virial Theorem (see derivation of Tuller Fisher, but now use σ instead of $v_{circular}$
- Recent scaling relations (Cappellari et al 2006) find $M=5R_e\sigma^2_e/G$

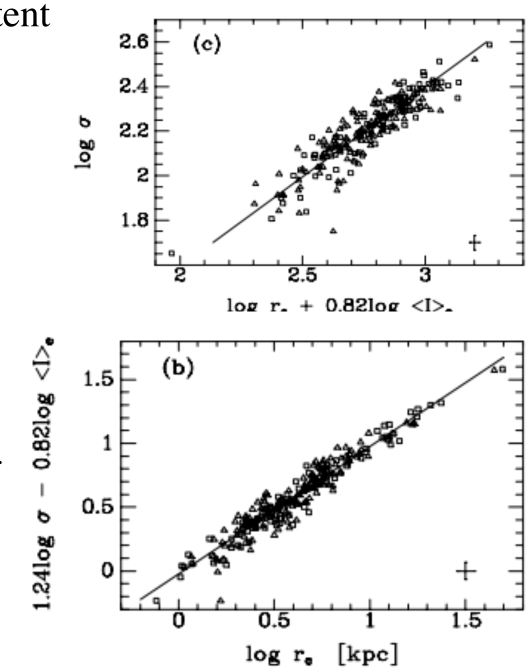
6 observables are all correlated via **the fundamental plane**
Luminosity, Effective radius,Mean surface brightness,
Velocity dispersion, metallicity, dominance of dispersion over rotation

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



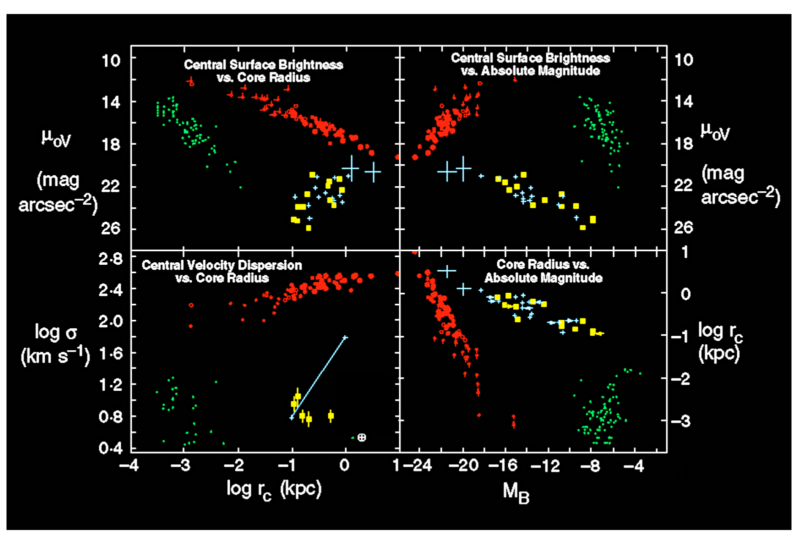
Three key observables of elliptical galaxies, effective radius Re, the central velocity dispersion σ, luminosity L (or equivalently the effective surface brightness $I_e = L/2\pi R_e^2$)

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.

- 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 ($\sigma, L = 2\pi I_e R^2_e$) 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.

Scaling Relations

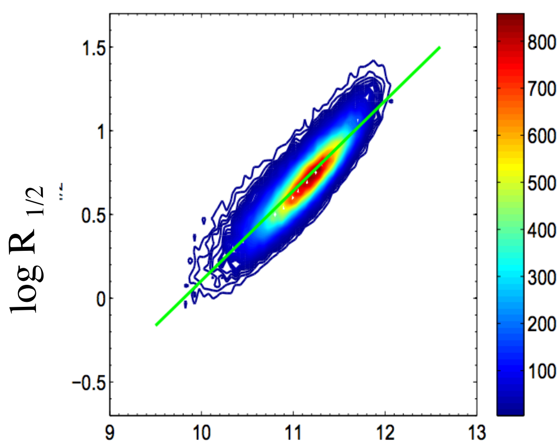
- There is a very strong relation between the size and stellar mass of normal elliptical galaxies with

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

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 big complex see discussion in MBW 597-600

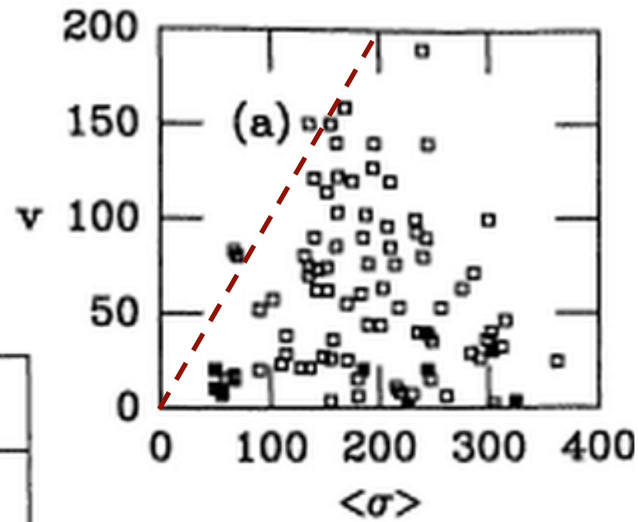


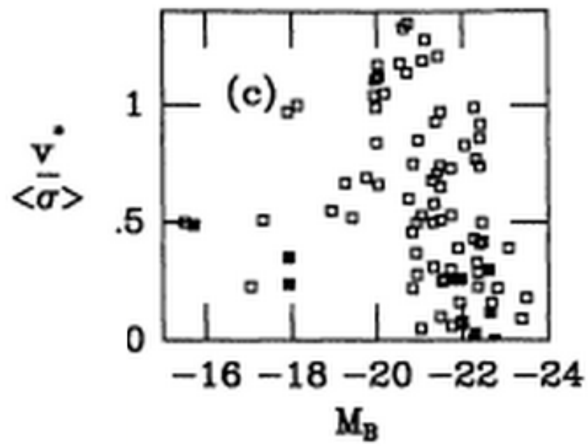
log $M_{stellar}$

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