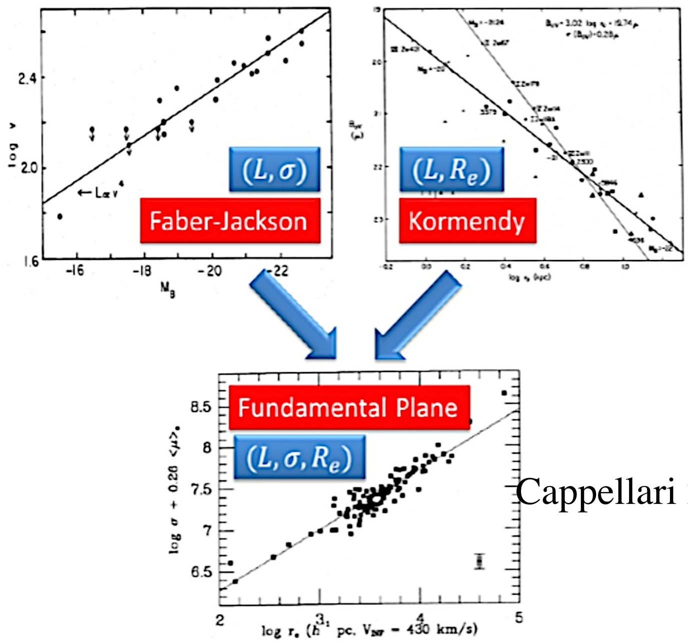
Spheroidal (Elliptical) Galaxies MBW chap 13, S+G ch 6

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

- Spiral galaxies bulges, while visually similar are physically different in many ways from E galaxies
- For very extensive review on Morphology see Buta 2013 arxiv 1304.3529



Cappellari 2014

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

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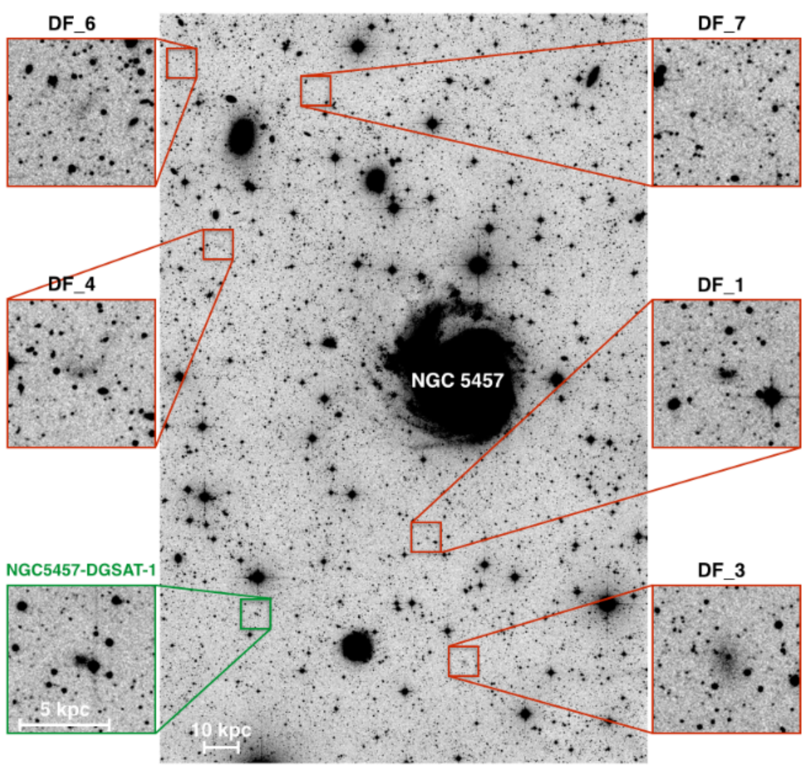
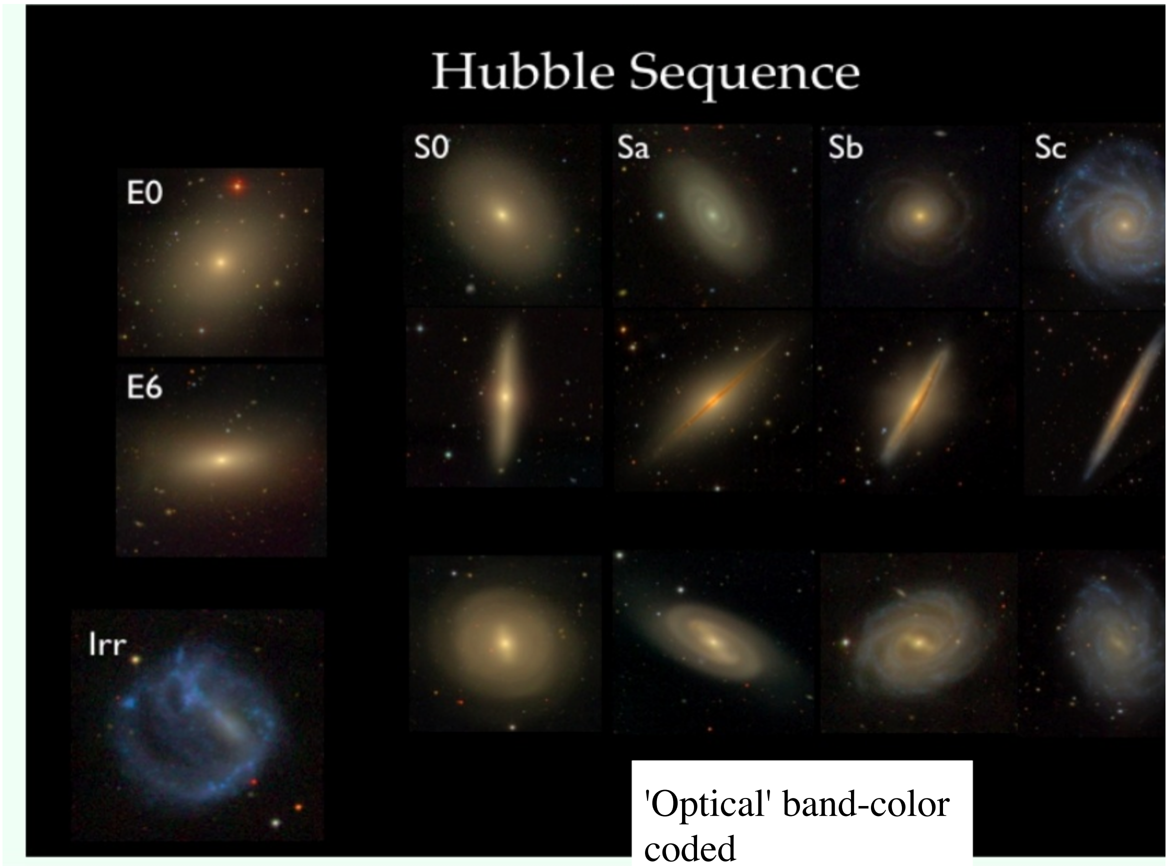
Todays Amazing Paper

DGSAT: Dwarf Galaxy Survey with Amateur Telescopes

I. Discovery of low surface brightness systems around nearby spiral galaxies
B. Javanmardi et al 1511.04446
DGSAT is a network of privately owned robotic observatories equipped with modest-sized telescopes (0.1-0.8-meter) located in Europe, the United States, Australia and Chile.

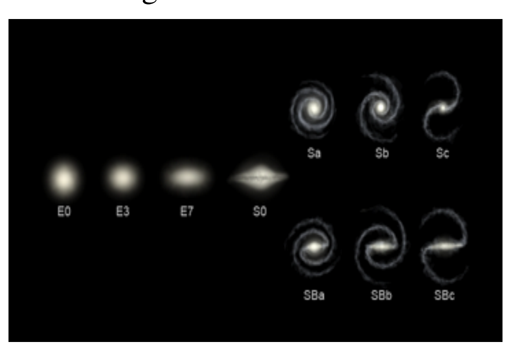




'Optical' band-color coded

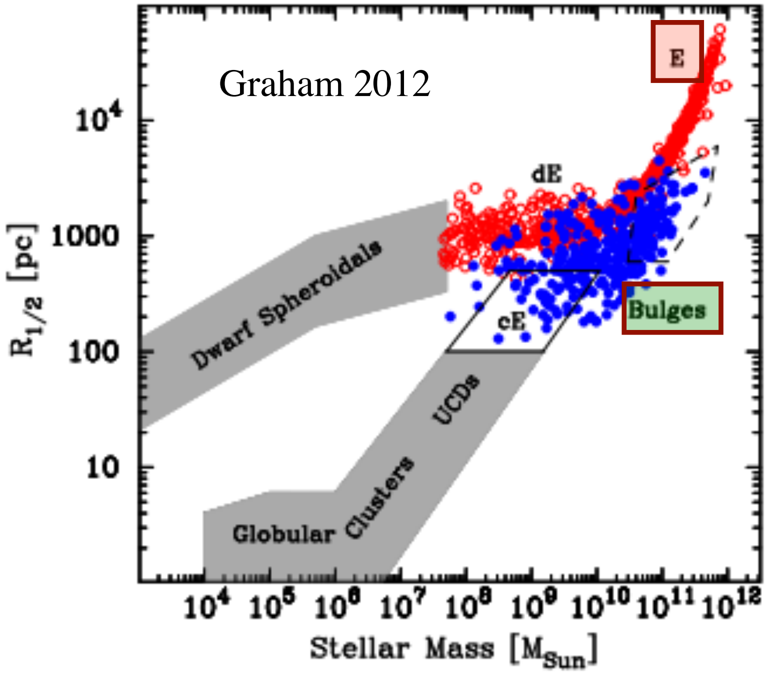
Spheroidal (Elliptical) Galaxies MBW chap 13, S+G ch 6

- Visual Impression: smooth, roundish- deceptively simple appearing- collisionless systems
- While visually 'similar' detailed analysis of spheroids shows **3** categories
  - Massive/luminous systems (M_B>-20): 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(-18<M_B<-20: **power law central brightness distribution**, little cold gas; as mass drops effective rotation increases, oblate, 'disky'
  - Dwarf ellipticals: no rotation, exponential surface brightness



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

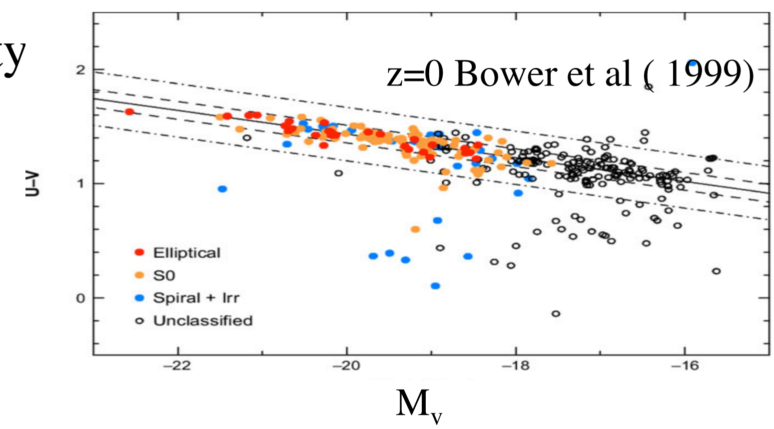
- Remember $R_{1/2}$ from the Sersic model for the surface brightness distribution

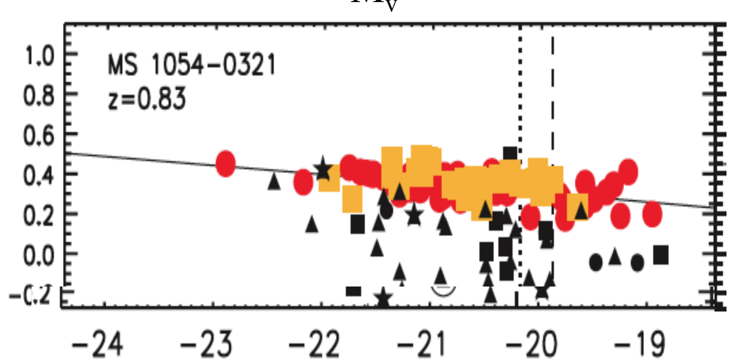


see for more details astr553/Topic07/Lecture_7.html

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

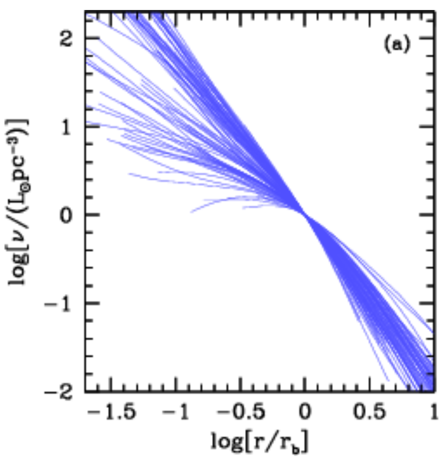


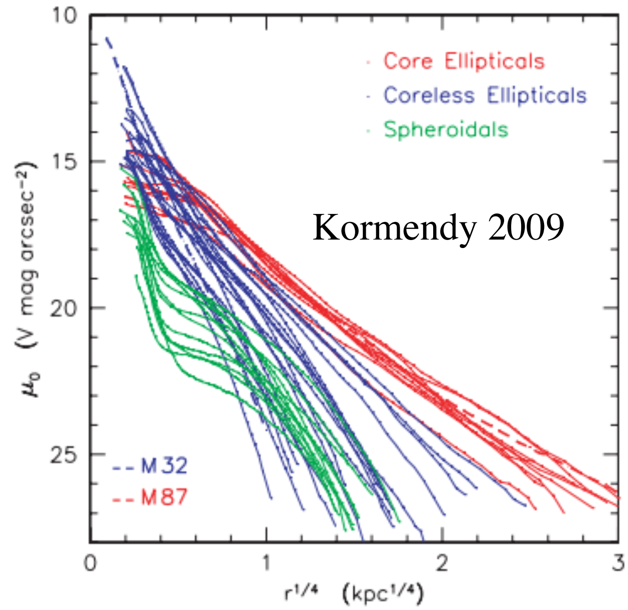


Renzini 2006 ARAA- Stellar population diagnostics of elliptical galaxy formation

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

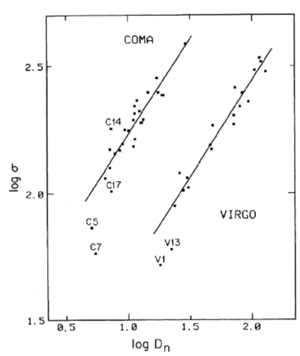
Fundamental Plane

Motivations: circa 1985 (Djorgovski)

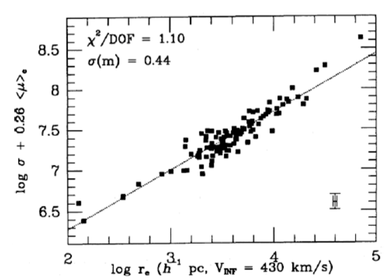
- How many statistically significant properties describe elliptical galaxies, and how are they related?
  - what is the "manifold of elliptical galaxies"?
- What is the "2nd parameter" in the F-J relation, so that it can be improved as a distance indicator for early-type galaxies (ala T-F relation)

The Initial Renderings

D_n-σ, Dressler et al. 1997



R-σ-μ, Djorgovski & Davis (1987)

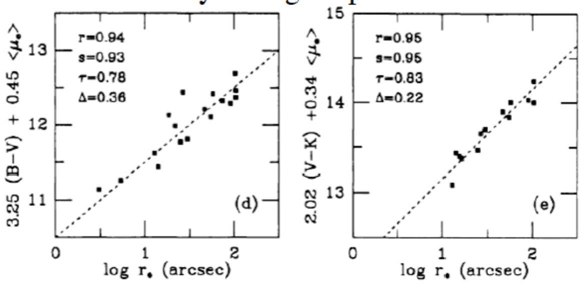


The "canonical form": $R \sim \sigma^A I^B$
R = non-isophotal radius (r_e, r_η, …)
σ = central proj. velocity disp.
I = mean surf. br. in linear units

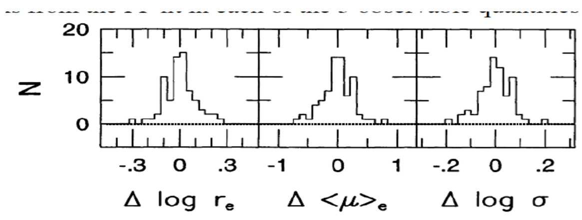
Best Representation

- Also see 'the plane' in metallicity and age

Metallicity and age dependent colors



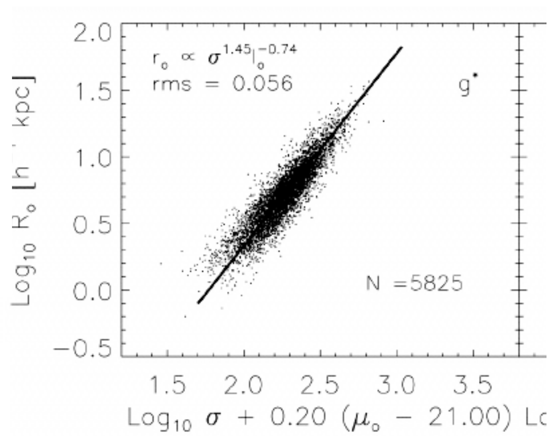
Remarkably small scatter



< 0.055   < 0.15   < 0.035

de Carvalho & Djorgovski 1989

$R_{eff} \sim \sigma_0^{1.53} \langle\Sigma\rangle_{eff}^{-0.79}$



Meaning

- Derive Fundamental plane scaling exactly as for the T-F relation.
- Galaxies are on a "Virial Theorem Plane" in the space of mass, mean density, and kinetic temperature
  - ***If*** galaxies represent a homologous family of structures ***and*** had

    (M/L) = const.,

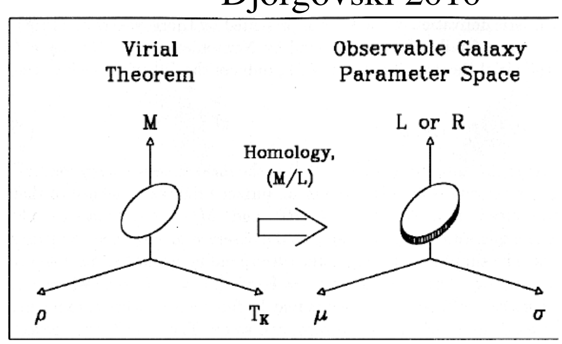
then they should follow the VTP:

$\boldsymbol{R} \sim \sigma^2 \boldsymbol{I}^{-1}$

Since they don't, and the observed FP scaling is: $\boldsymbol{R} \sim \sigma^{1.4} \boldsymbol{I}^{-0.8}$,

- either one or both of these assumptions must be broken

Djorgovski 2010



In elliptical galaxies many of their properties are tightly coupled the dynamical structure,chemical enrichment (star formation) history, and growth of their central black holes, in a remarkably robust manner, with just two parameters accounting for many fundamental properties

- The small scatter of the FP implies that ellipticals cover only a very limited, standardized range of dynamical structures

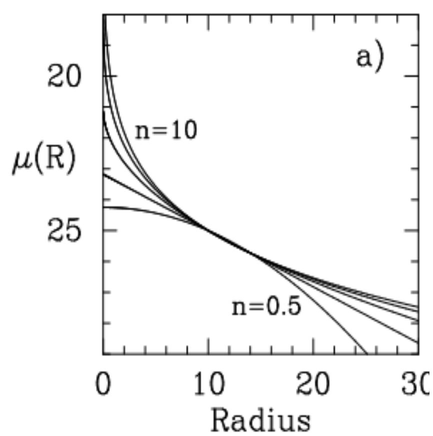
Modern Interpretation-the ***mass-based F-P***

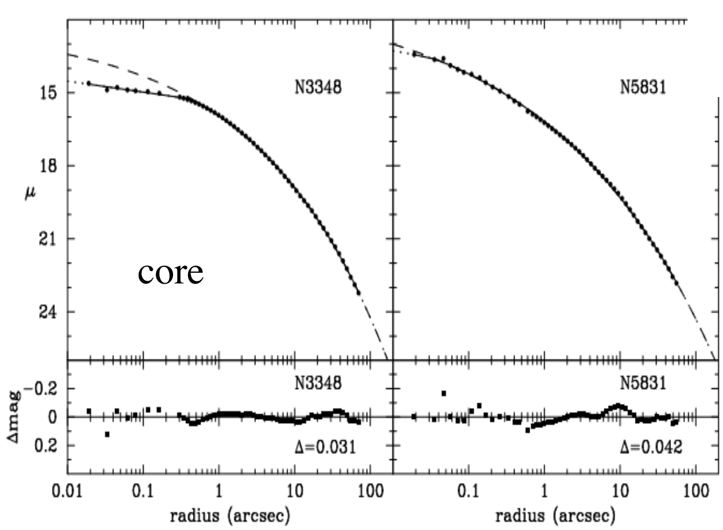
- Please read

The ATLAS^{3D} project - XX. Mass-size and mass-σ distributions of early-type galaxies: bulge fraction drives kinematics, mass-to-light ratio, molecular gas fraction and stellar initial mass function 2013MNRAS.432.1862 Cappelari et al

Fit of Sersic Profile

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



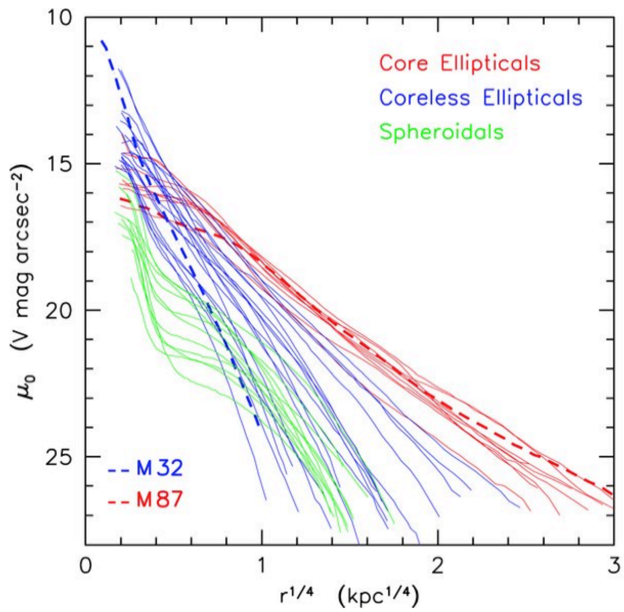


For n=4 (the deV model the total luminosity (S+G problem 6.1) is $7.22\pi R_e^2 I(R_e)$ and <u>half the light comes from within R_e</u>

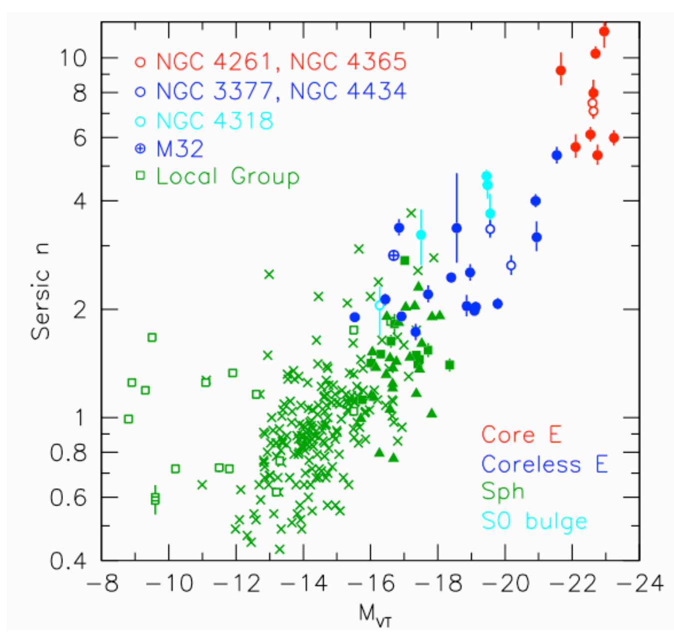
Surface Brightness Distribution of E Galaxies

why is a core a big deal?

- a core is a flattening of the surface brightness profile towards the center
- however theoretical Cold dark matter only profiles do not have a core.
  - either a core is a sign that the potential differs from CDM predictions OR
  - the sign of baryonic physics



Systematic Trend in Sersic Parameters with Luminosity



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)

Seems likely that both dissipational collapse and mergers are likely involved in the formation of elliptical galaxies

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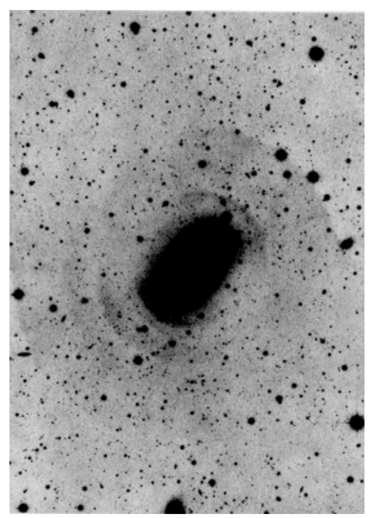
Deviations from Sersic

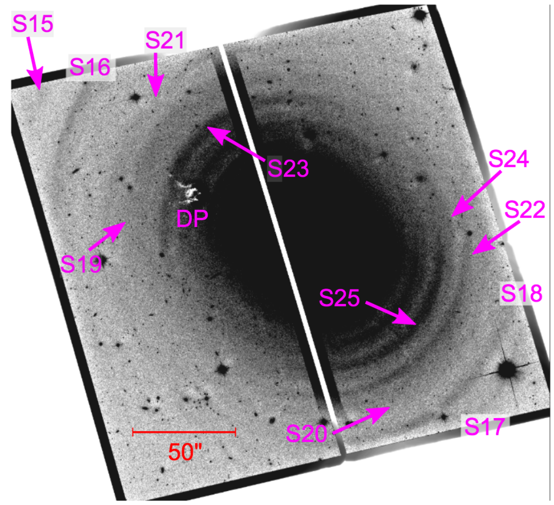
- ~10-20% of ellipticals show 'ripples/shells'- indicative of a merger (MBW ***13.3.5 Merging Signatures)***



But such fine structures form only when the merger involves at least one dynamically cold progenitor (disk or dwarf galaxy);
mergers between two dynamically hot systems (i.e. between two ellipticals) do not produce shells and ripples, because the intrinsic velocity dispersion is too high

Shell Formation

- Schweiver (1983) –small galaxy colliding with larger one
- Small galaxy completely tidally disassociated the stars from that galaxy oscillate independently in the potential well of the new system (dominated by the elliptical) on more or less radial orbits
- They spend most of their time at the apocenters- the shells
- The wrapping in phase space (stars with smaller periods have more oscillations) give the multiple shells (Quinn 1984)



NGC3923 Bilek et al 2015

The "Complete" List of Parameters- Kormendy and Bender

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

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

(2) rotate slowly, rotation is unimportant dynamically

(3) are moderately anisotropic and triaxial;

(4)low ellipticity

(5) have boxy-distorted isophotes;

(6) have Sersic (function outer profiles with $n \geq 4$;

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

(8) often contain strong radio sources,

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

Normal and dwarf true ellipticals (M_V>-21.5)

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

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

(3) are nearly isotropic and oblate spheroidal,

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

(5) have disky-distorted isophotes;

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

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

(8) rarely contain strong radio sources, and

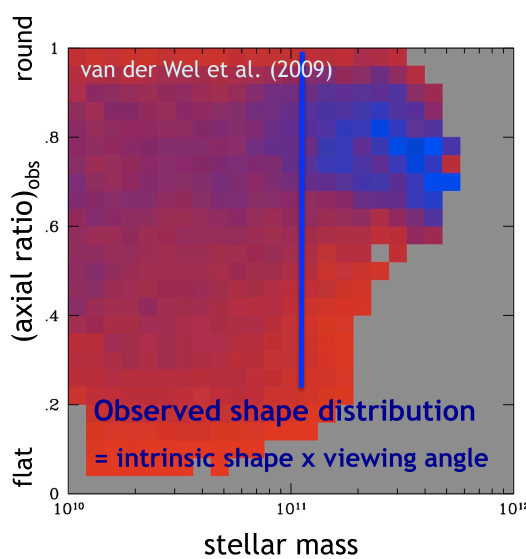
(9) rarely contain X-ray-emitting gas.

The shapes of Early-Type Galaxies

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

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

At high mass systems more uniform



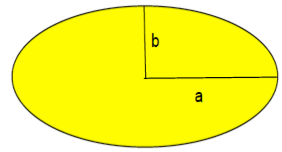
Ellipticals -Shape

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

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

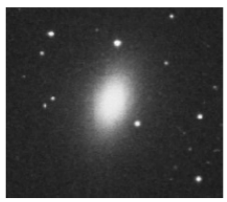
Apparent ellipticity
n=10(a-b)/a
=> En

Observe E0 (round) to E7



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

M87 (E0)

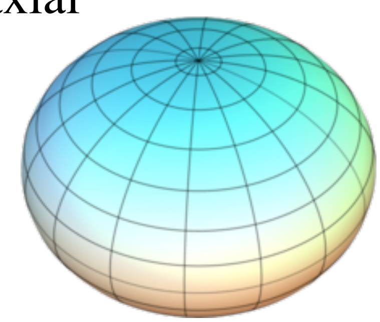


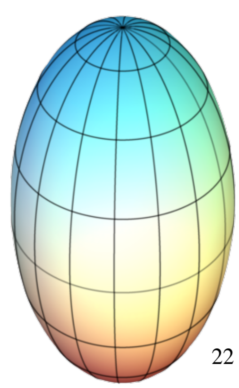
M59 (E5)

E7

Oblate, Prolate Triaxial

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





Ellipticals -Shape

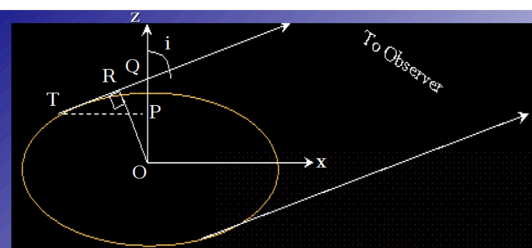
- Shape alone cannot tell us what is going on
- Triaxial ellipsoids:
  - $[x^2/a^2]+[y^2/b]^2+[z^2/c^2] = 1$
- From morphology alone can't tell if elliptical galaxies are

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

Ellipticals Shape

So an observer looking along the z axis would see an E0 (round) galaxy, when viewed at an angle you would see an elliptical shape with apparent axis ratio q = b/a. Looking at the tangent point to the elliptical surface (T) the coordinates of this point are

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



If elliptical galaxies are oblate spheroids then

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

Distribution of B/A

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

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

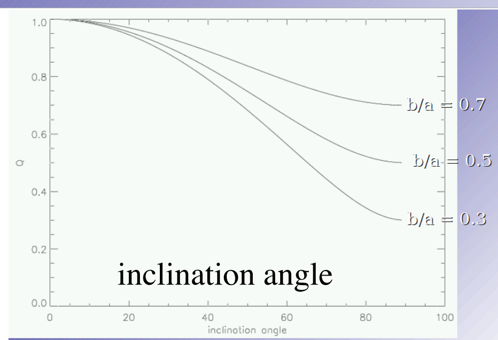
Using our definition of m for the last step. Finally we can rewrite this as

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

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

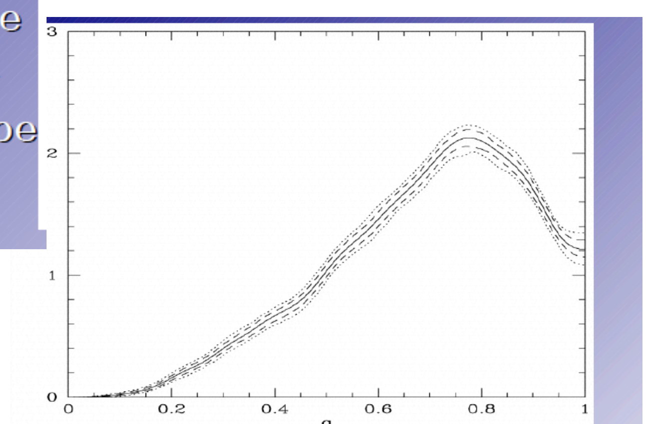
$$q_{prol}^2 = (b/a)^2 = [(B/A)^2\sin^2(i) + \cos^2(i)]^{-1}$$

q



Ellipticals are Triaxial

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



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

Shape could also be due to rotation around z axis.

Density Profile

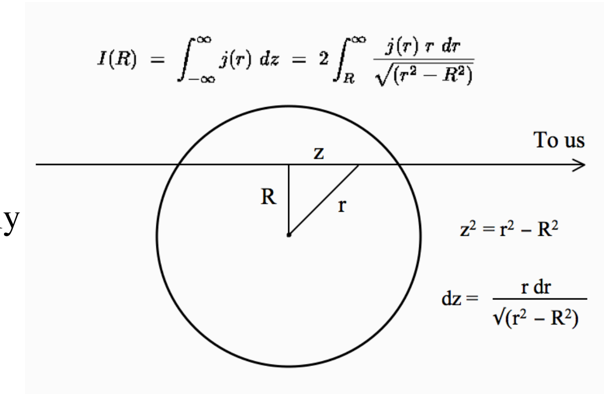
- I(R) is the projected luminosity surface brightness, j(r) is the 3-D luminosity density (circular images- if image is elliptical no general solution)

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

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

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

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



While the Sersic model is a better fit to the surface brightness profiles it is not easily invertable to density-often use a generalized King profile with surface brightness $I(r)=I(0)(1+(r/r_c)^2)^{-5/2}$ which gives a density law $\rho(r)=\rho(0)(1+(r/r_c)^2)^{-3/2}$ where $r_c=3\sigma/\mathrm{sqrt}(4\pi G p_c)$

Ages of Elliptical Galaxies

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

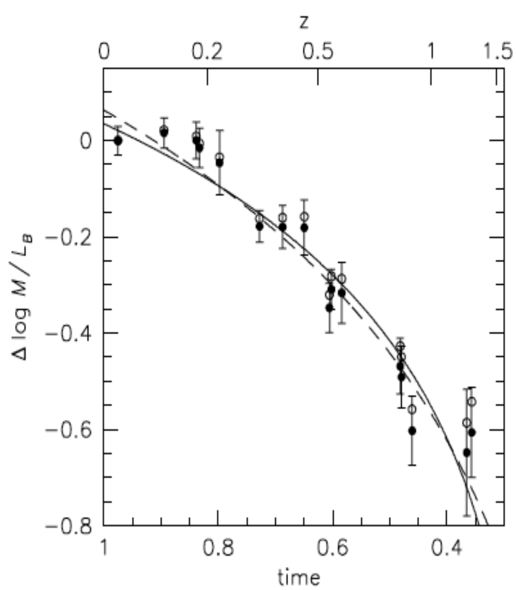
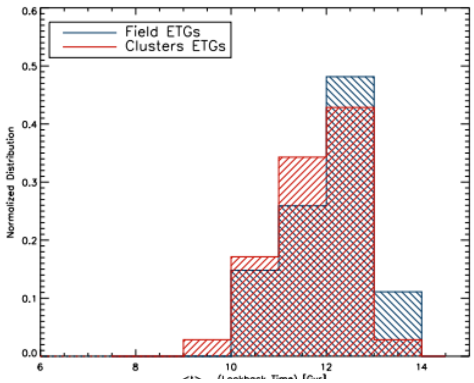


FIG. 8.— Evolution of the mean M/L_B ratio of massive cluster galaxies with time. Open symbols are the same datapoints as shown in Fig. 6. Solid symbols with errorbars are offset by $-0.05 \times z$ to account for progenitor bias (see text). The solid line shows the best fitting model for a Salpeter-like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

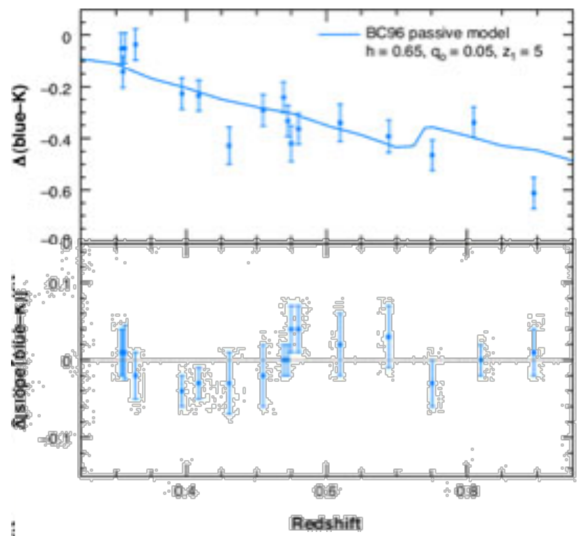
Higher z observations constraint on origin

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



6 8 10 12 14

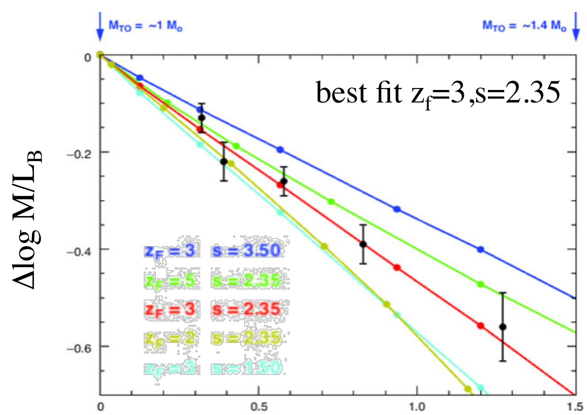
look back time of star formation (gyrs)



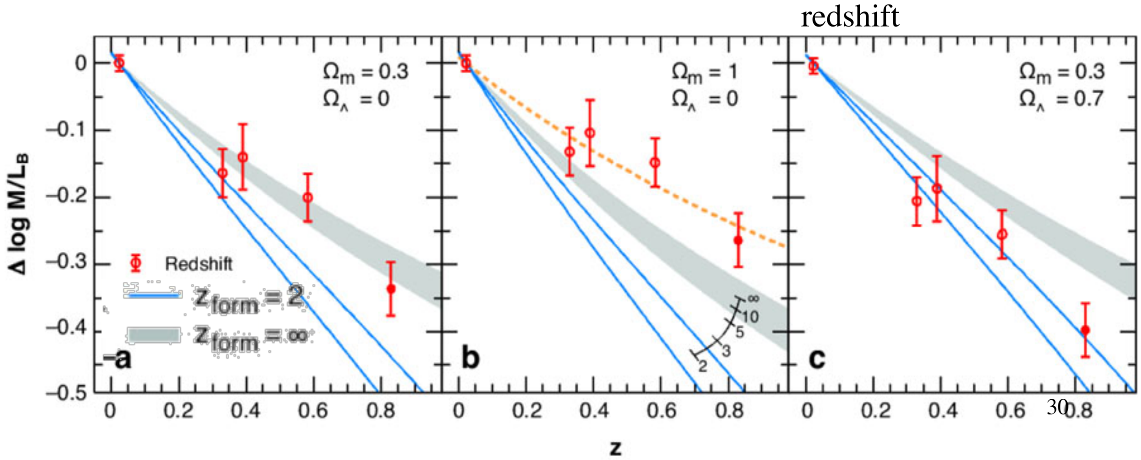
using the consistency of the colors of these galaxies with 'passive' evolution the ages of massive ellipticals in clusters is ~10-13Gyr (!)- Rettura et al 2012

Evolution of Elliptical Galaxies

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

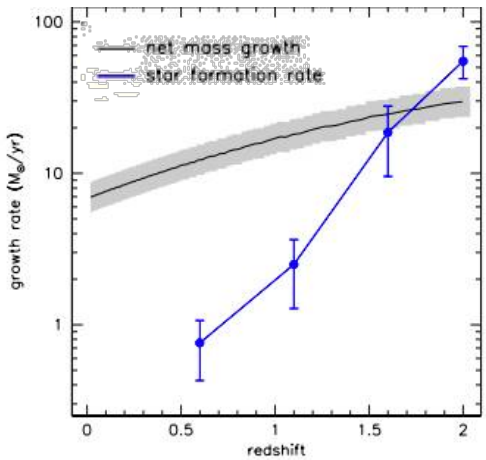


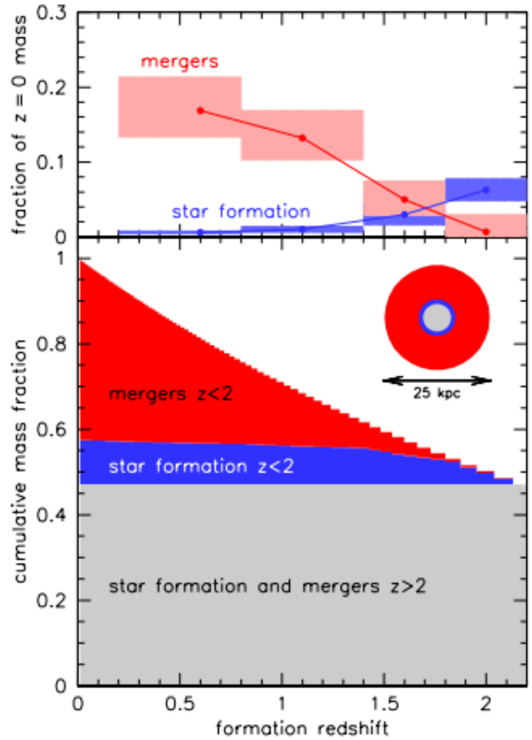
redshift



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

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

Thursday Dec 17   10:30 am - 12:30 pm   this room

deadline for project Dec 9

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

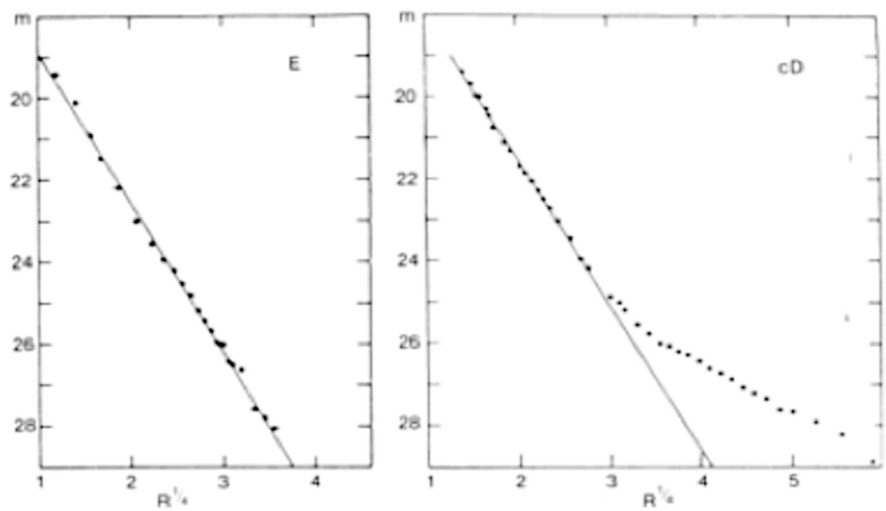
isotropic oblate flattened spheroids

'coreless'- power law inner slopes

smaller Sersic indices

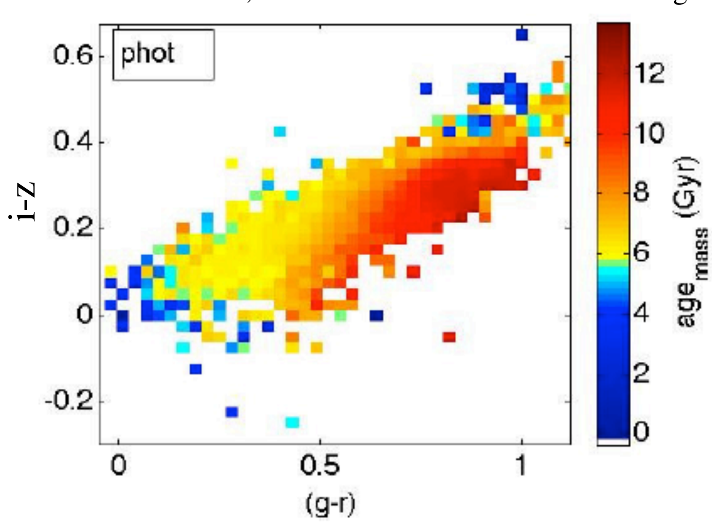
Special Objects-The most massive systems

- '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.
- inner portions of the BCGs are formed outside the cluster, but interactions in the heart of the galaxy cluster grow and extend the envelopes of the BCGs.



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.

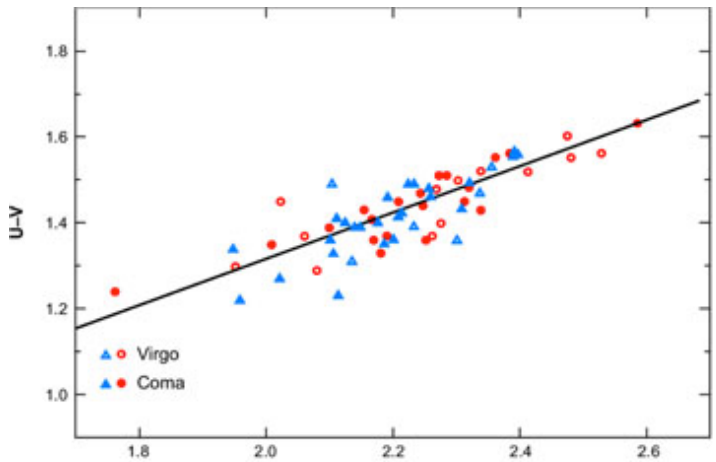


Color-color plot
Graves et al 2010

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,

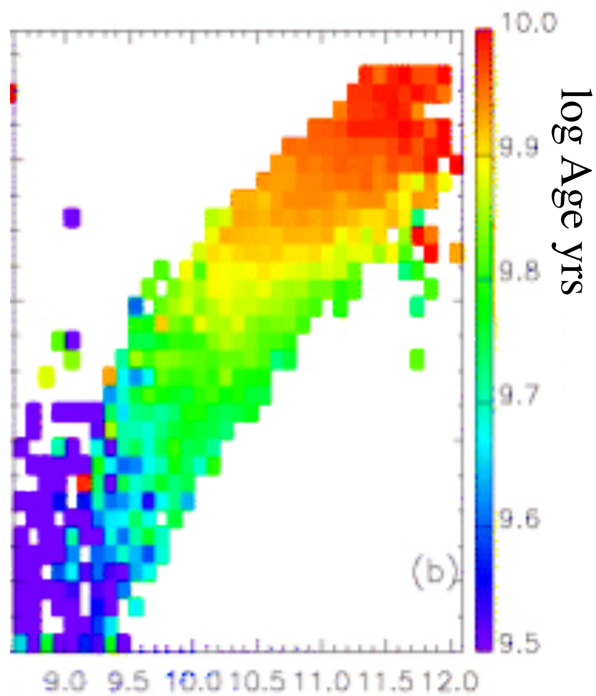


log σ

Bower, Lucy, Ellis 1991

More Massive Galaxies are Older

- small but systematic trends for more massive and luminous galaxies tend to be older (Graves et al 2010)

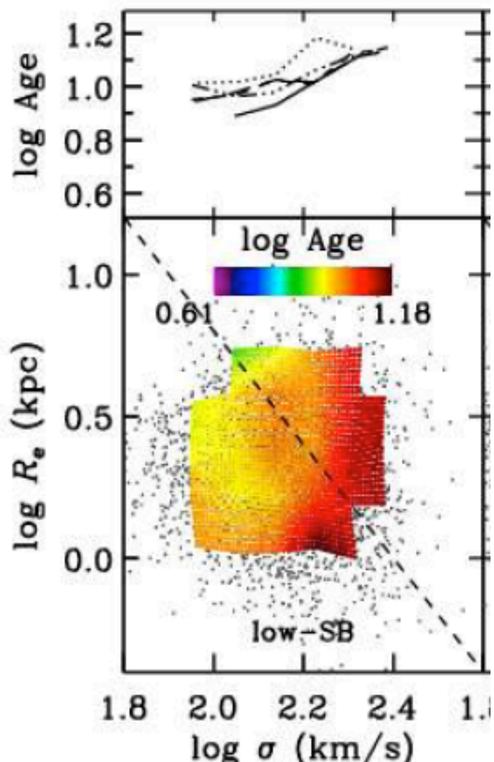


$\log M/M_\odot$

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*

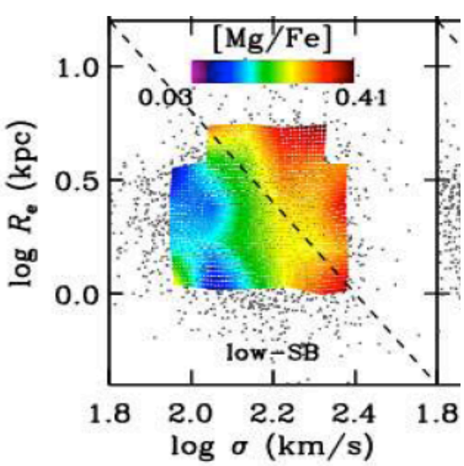
Strong connection of chemical composition structural parameters, mass, age...
Strong clues to how stars/ galaxy form...

- 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.

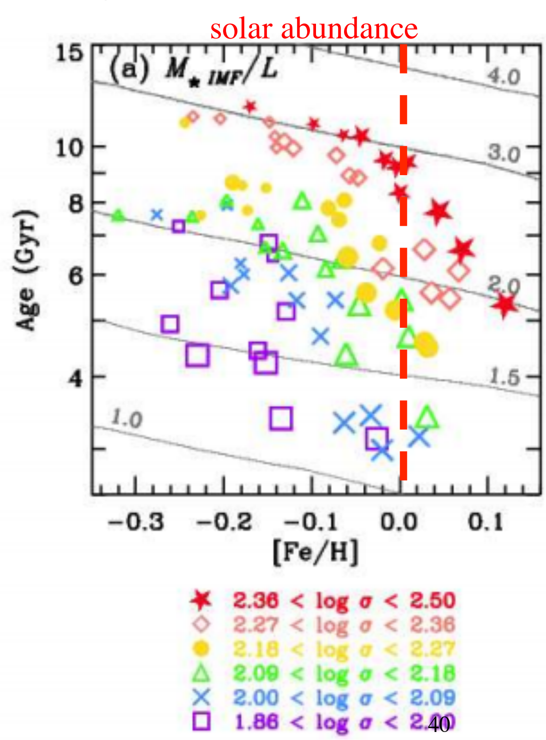


Metallicity

- 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



Modeling the Data

- Modern numerical models of ellitptical galaxy formation (Porter et al 1407.2186)
- They find that the strong correlations with velocity dispersion stems from the the small change in galaxy velocity dispersion from its formation to the present day while large number of minor mergers wash out correlations with radius.

- and at a fixed halo mass, galaxies above the FP have had more effective star formation ß

Modeling the Ages and Metallicities of Early-Type Galaxies in Fundamental Plane Space 11

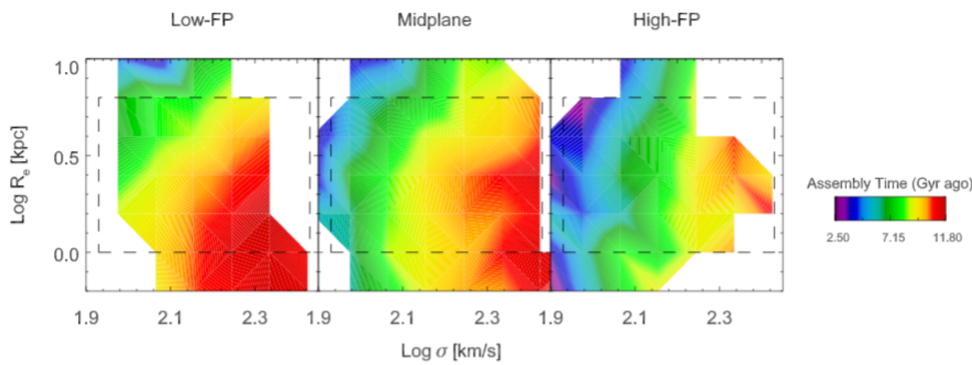


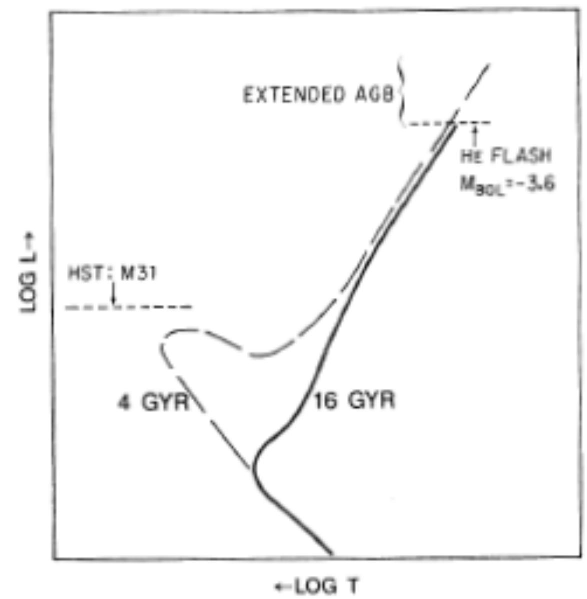
Figure 7. Relation between the time since the galaxy was assembled (became spheroid dominated), effective radius, and velocity dispersion for early type galaxies. The different panels represent the three central slices of the FP, as shown in Figure 2. Early type galaxies that were ssembled earlier have higher velocity dispersions and tend to fall below the FP.

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

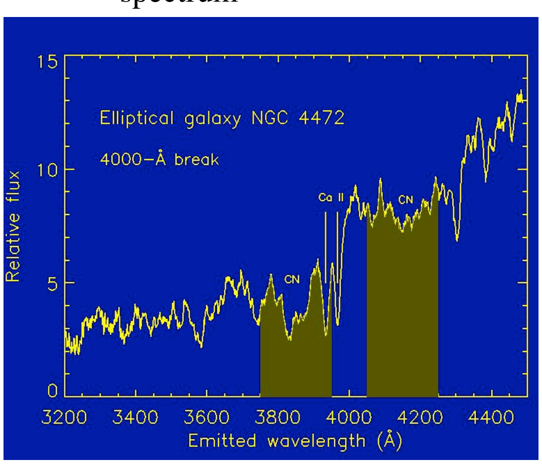
- The problem is that most of the stellar light is from giants but most of the mass is on the Main Sequence
- On the giant branch there is not much difference between 4 and 16Gyr aged populations

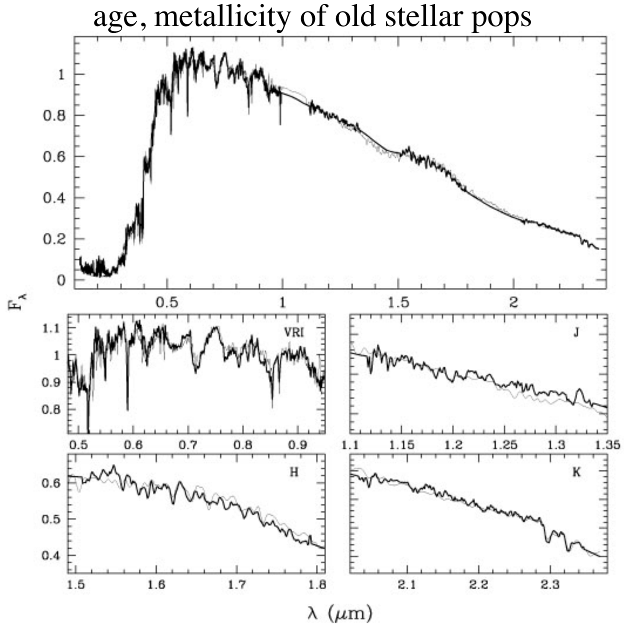


Spectrum of Ellipticals

- 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

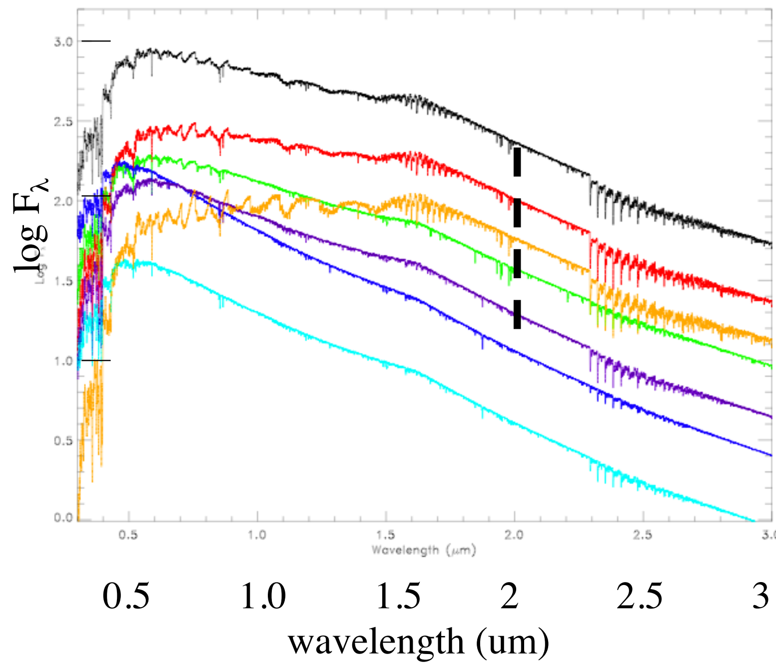




see GuyWorthy's web page http://astro.wsu.edu/worthey/dial/dial_a_model.html

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

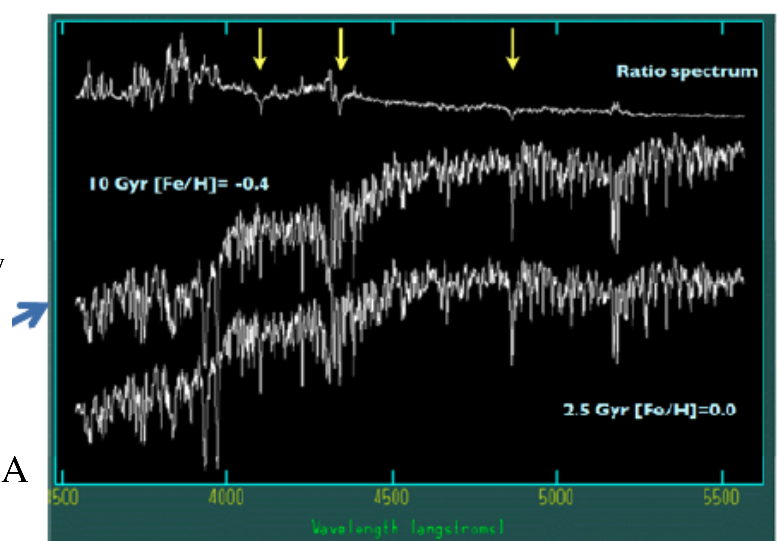


Age Metallicity Degeneracy

- 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

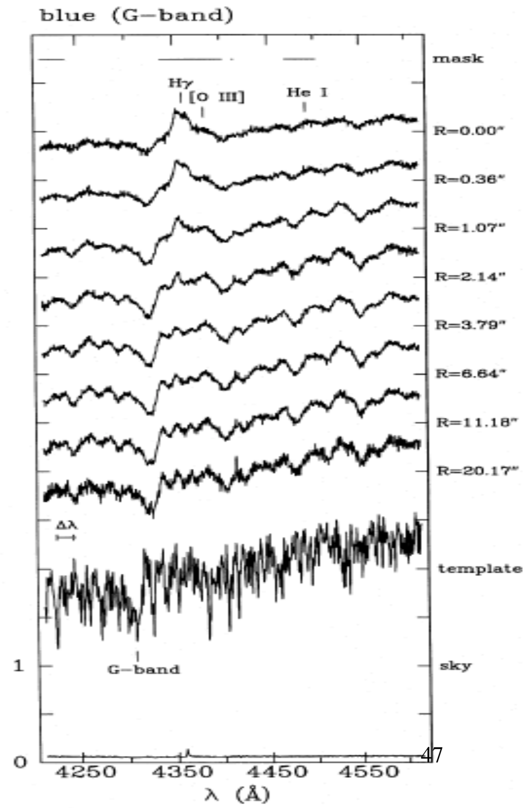


Vazdekis et al. (2007) models from MILES library

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.

2 CONROY, GRAVES & VAN DOKKUM

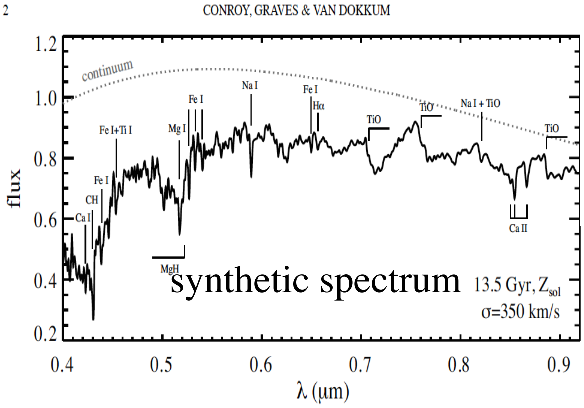


Figure 1. Model spectrum for an age of 13 Gyr and solar metallicity. The spectrum has been smoothed with a velocity dispersion of $\sigma = 350\ \mathrm{km\,s^{-1}}$, equal to the smoothing applied to the early-type galaxy data analyzed in this paper. Strong features are labeled. Also included is the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

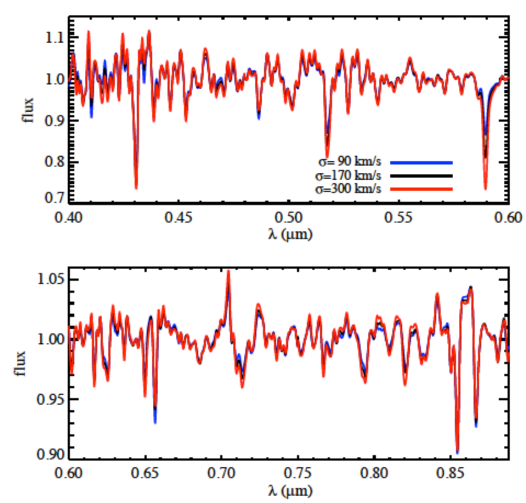
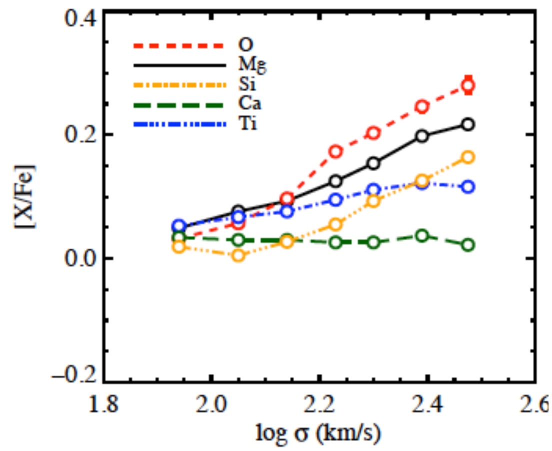


Figure 7. Continuum-normalized stacked spectra of SDSS early-type galaxies in three velocity dispersion bins.

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

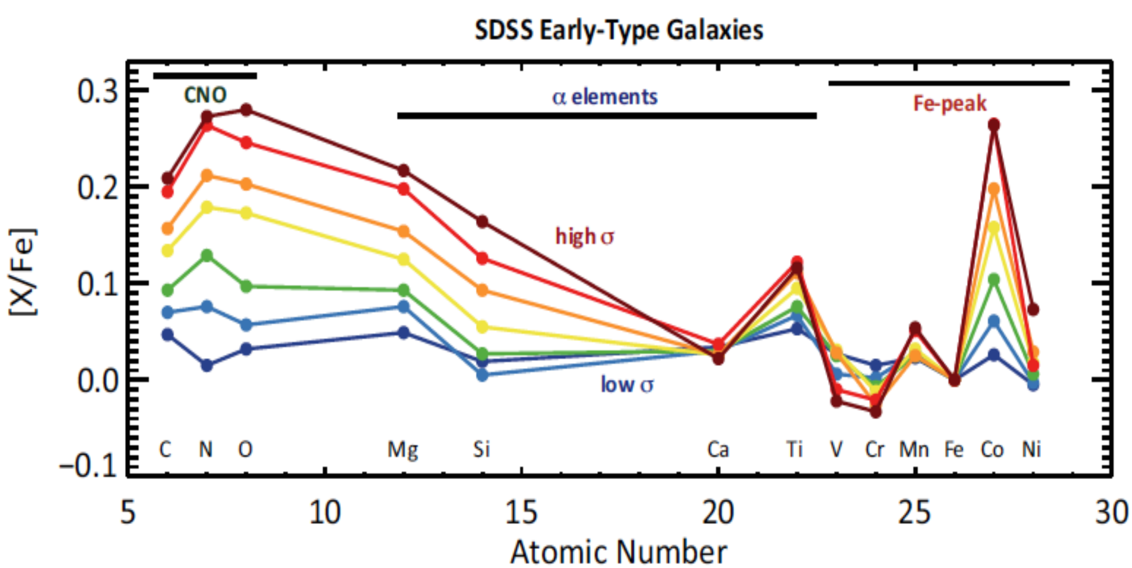
Metallicity

- 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



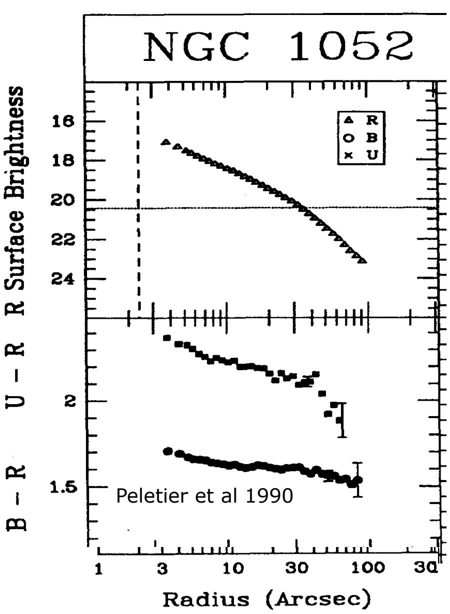
Conroy et al 2014

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

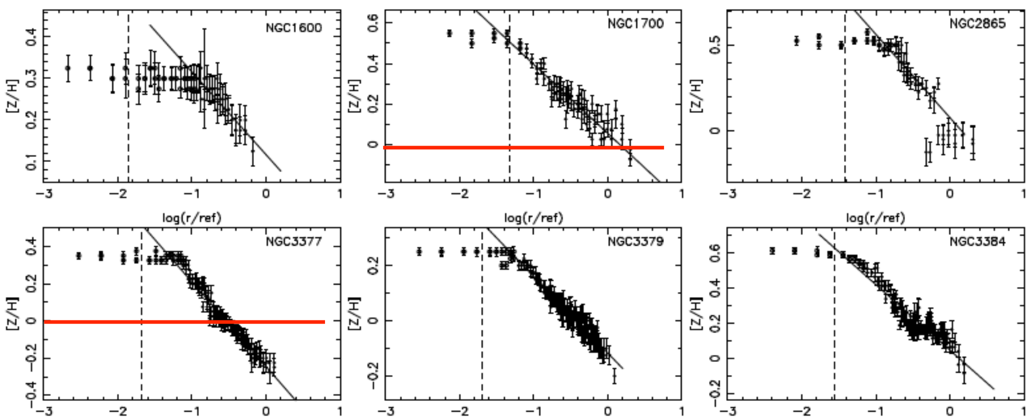
- Almost all galaxies become bluer outward- mostly due to decreasing metallicity



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

Stellar Abundance gradients

P. Sánchez–Blázquez et al.



Loubser et al 2012

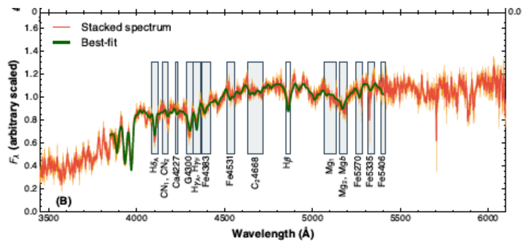
- stellar abundance drops with radius~ factor of 2, dZ/logr~-0.3 but optical data only extend to ~R_{e-} xrays go further out
- Super solar values in centers
- Weak age gradient

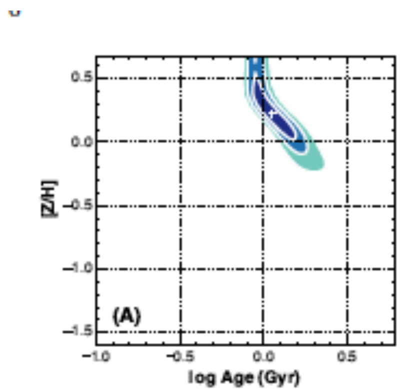
Summary of Abundance Data

- 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

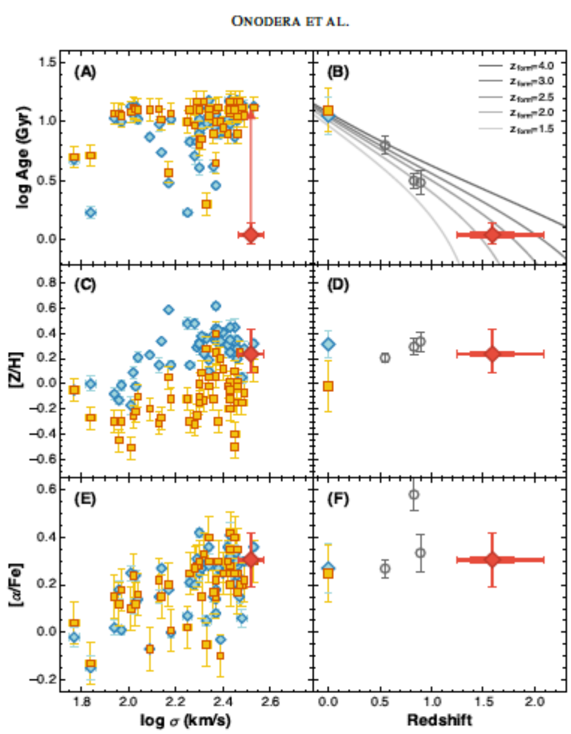
What About at Higher Redshift

- Ondera et al 2015ApJ...808..161 have studied massive quenched galaxies at 1.25< z< 2.09
- They find that these quenched galaxies if evolved passively to z = 0, would have stellar population properties in excellent agreement with local counterparts at similar stellar velocity dispersions, which qualifies them as progenitors of local massive early-type galaxies.
- Redshift evolution of stellar population ages suggests a formation redshift of $\{z\}_f \sim 2.3$,
- The measured [α/Fe] value indicates a star formation timescale of ≲ 1 Gyr, which can be translated into a specific star formation rate of ≃ 1 $\{\{Gyr\}\}^{-1}$ prior to quenching





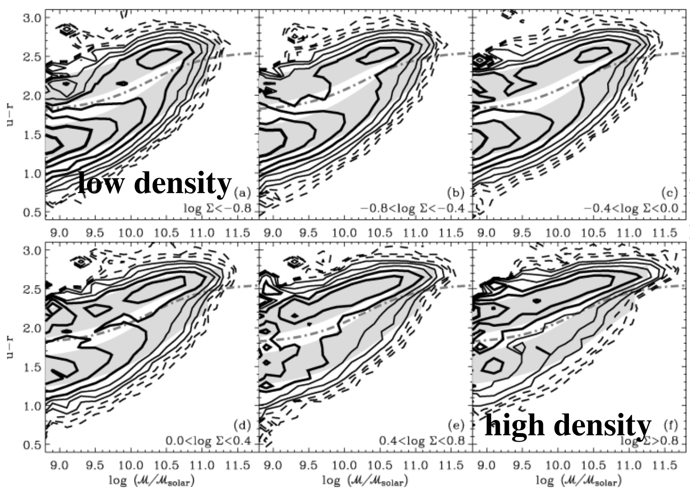
- The red arrowhead in panel (A) shows the ending point of a purely passive evolution at z= 0.
- Supporting the idea that that the build-up of quiescent galaxy populations with high velocity dispersions was
- largely completed by z 1.5.



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).