New Topic

- Formation and evolution of elliptical galaxies

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 many ellipticals formed from mergers and thus the age of the galaxy and the stars can differ.

mass to light ratio of an Aging SSP vs da

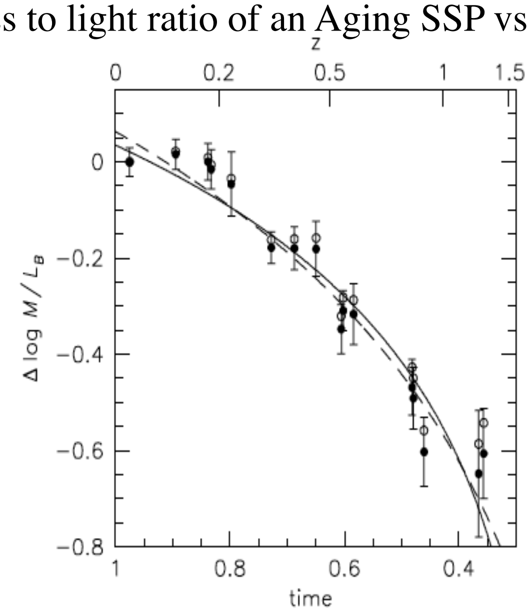
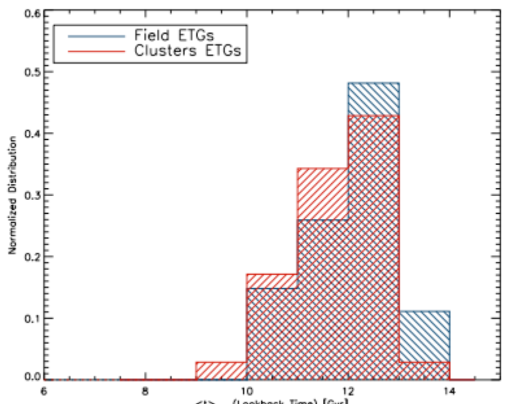


FIG. 8.— Evolution of the mean M/L_B ratio of massive cluster galaxies with time. Open symbols are the same datapoints as shown in Fig. 6. Solid symbols with errorbars are offset by $-0.05 \times z$ to account for progenitor bias (see text). The solid line shows the best fitting model for a Salpeter-like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

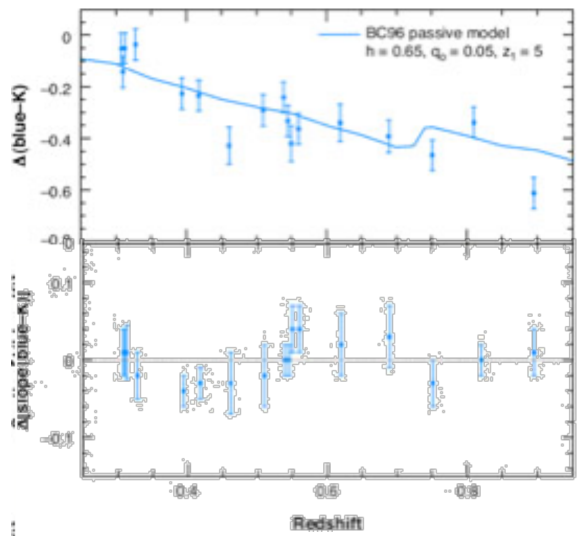
Higher z observations constraint on origin

- 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

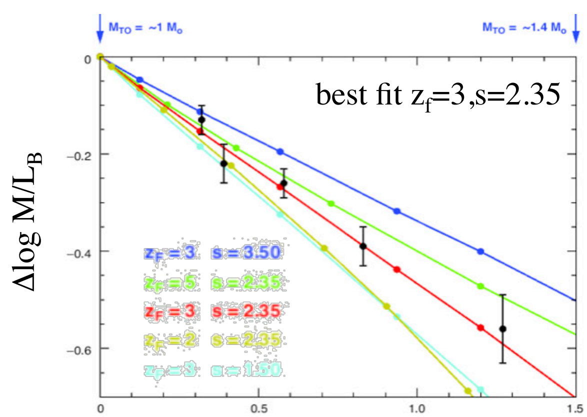
look back time of star formation (gyrs)



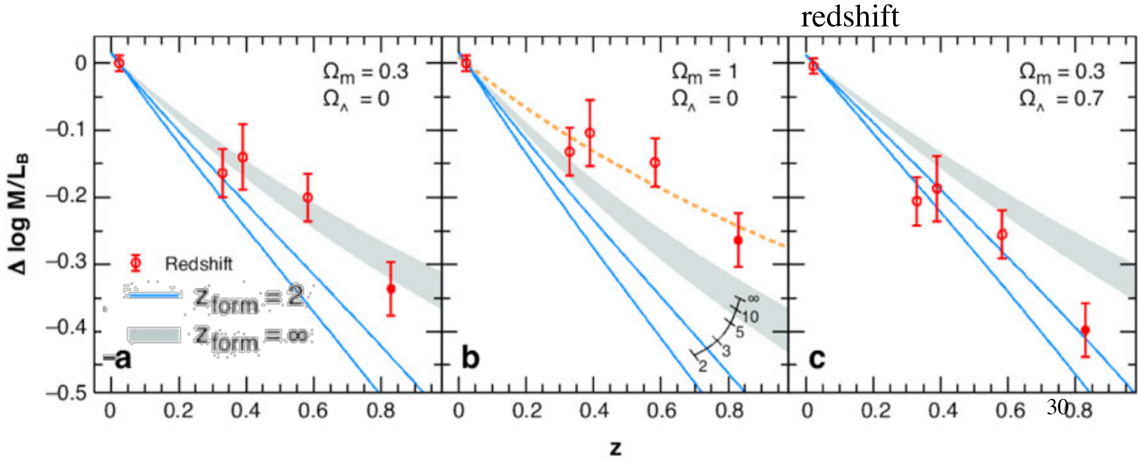
consistency of the colors of these galaxies with 'passive' evolution -ages of massive ellipticals in clusters is ~10-13Gyr (!)-Rettura et al 2012

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 (S) and formation redshifts:

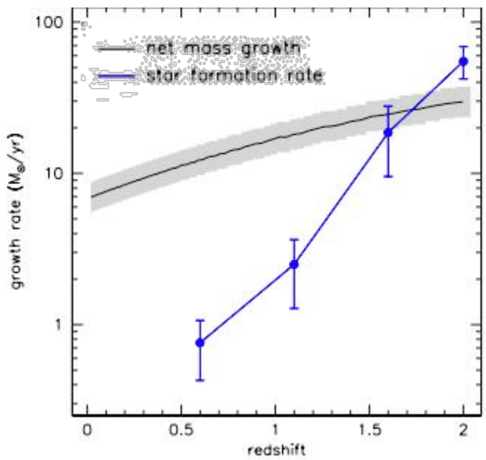


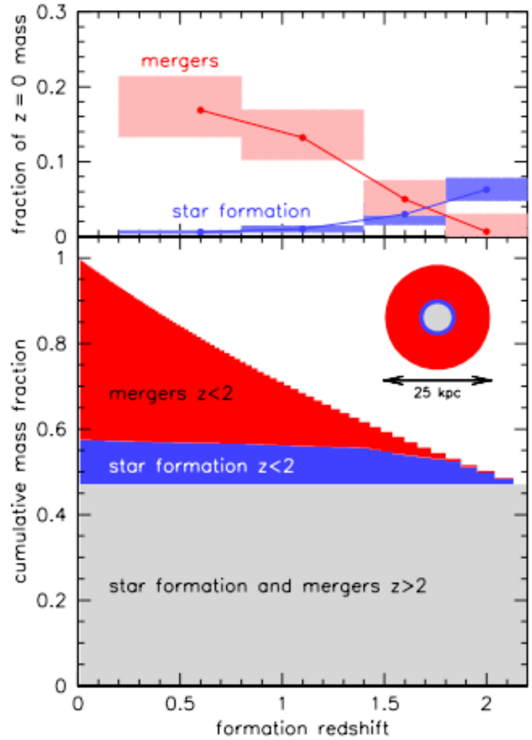
redshift



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)





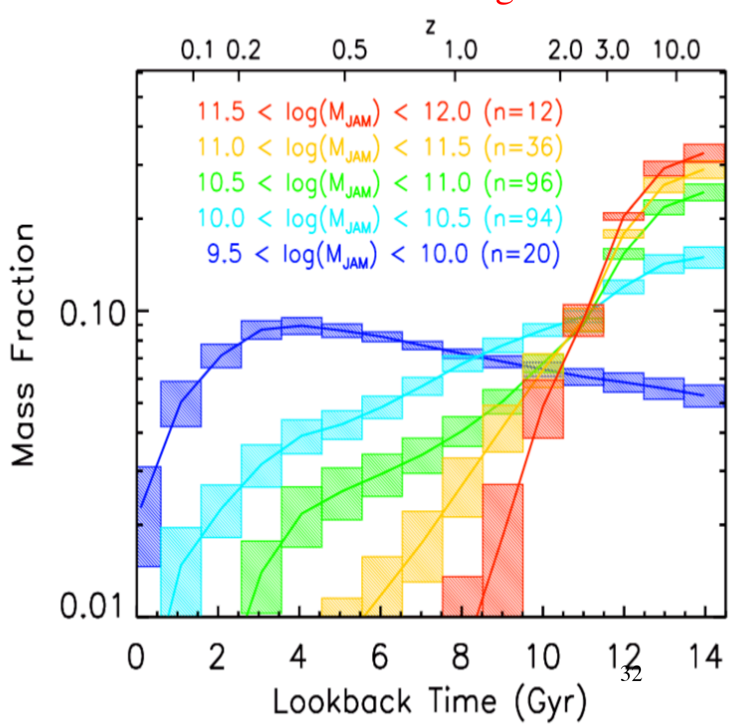
van Dokkum et al 2010

How Do Ellipticals Grow??

- Massive ones (red) form first at very high z- the lower the mass the lower the average redshift of formation (McDermid 2015)
- Definition of age is
  - the relative fraction of stellar mass formed at each epoch,

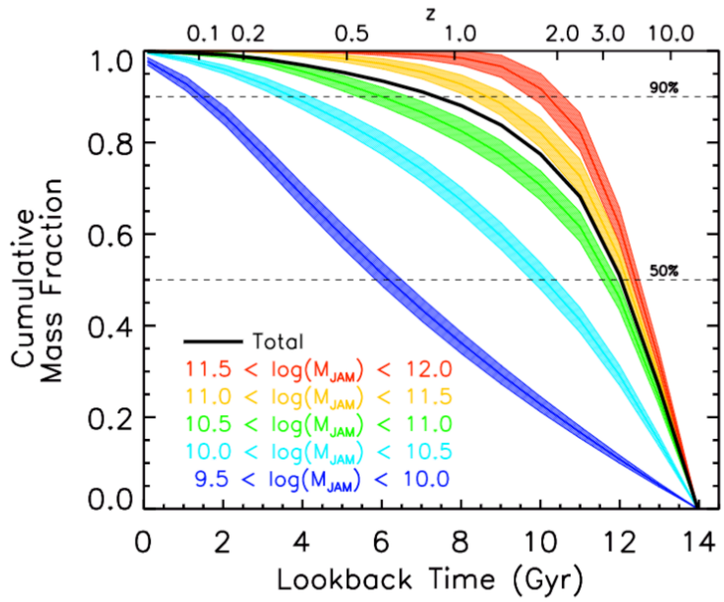
blue= low mass

red= high mass



How Do Ellipticals Grow??

- The integral of the previous slide- e.g. 90% of all galaxies more massive than Log $M_{star} > 11.5 M_{\odot}$ have completed their growth before z=2 (3 Gyr after the big bang)
  - smaller galaxies keep on growing today



(McDermid 2015)

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!

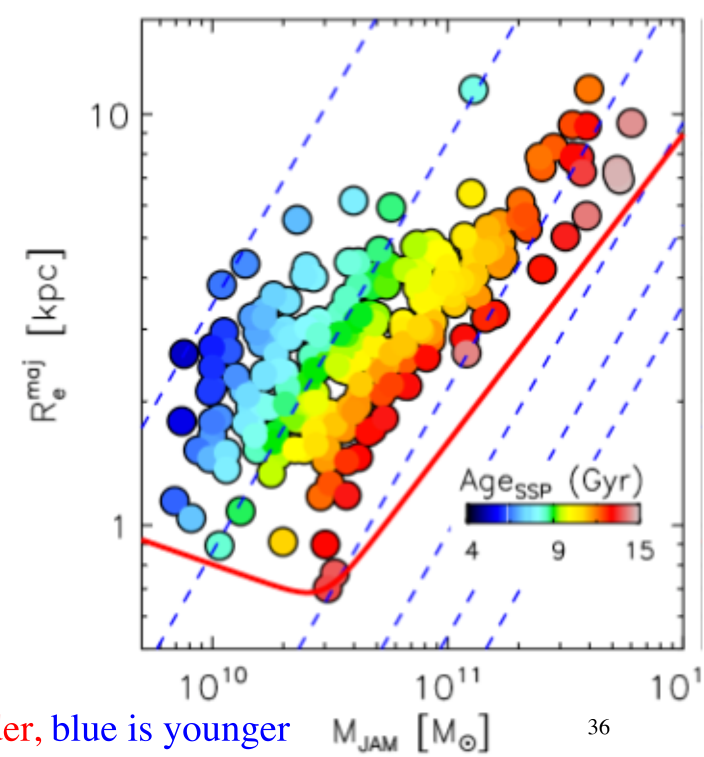
Notice correlation of dynamical properties and morphology

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

Age is Also Related to Mass and Size

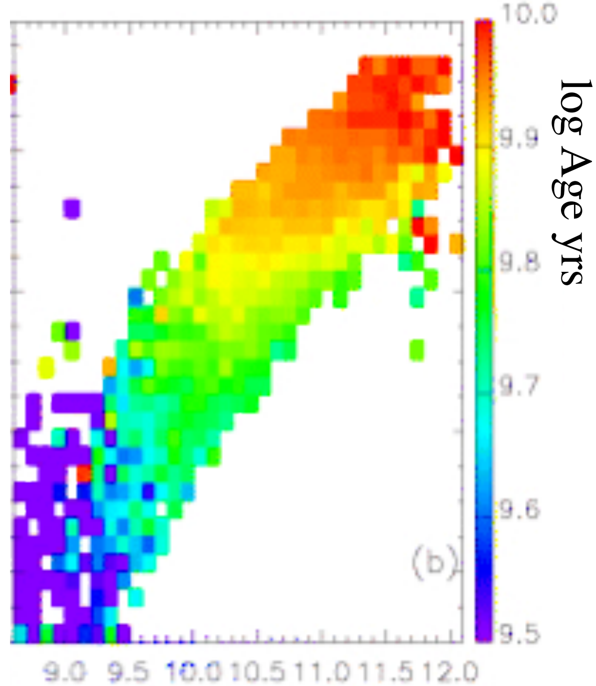
- More massive galaxies are, on average older (McDermid et al 2015)
- This is 'backward' from simple ideas of hierarchical galaxies formation where small things form first!!



redder is older, blue is younger

More Massive Galaxies are Older

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

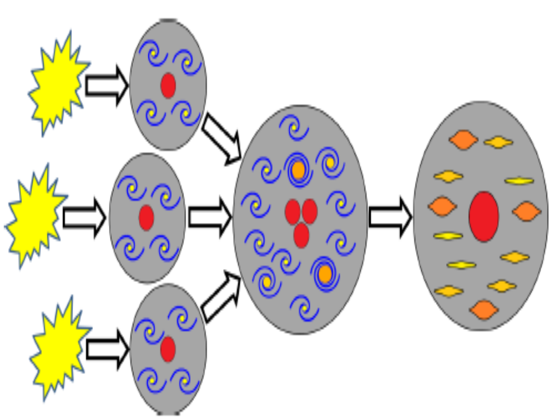


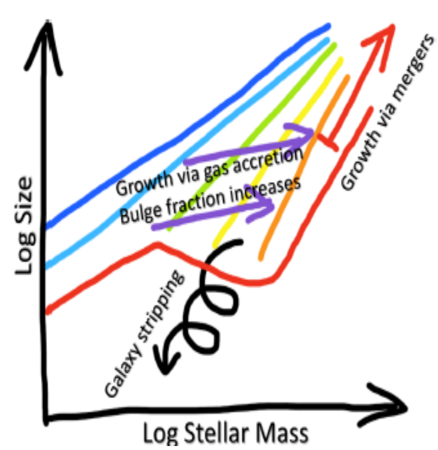
log $M/M_{\odot}$

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.

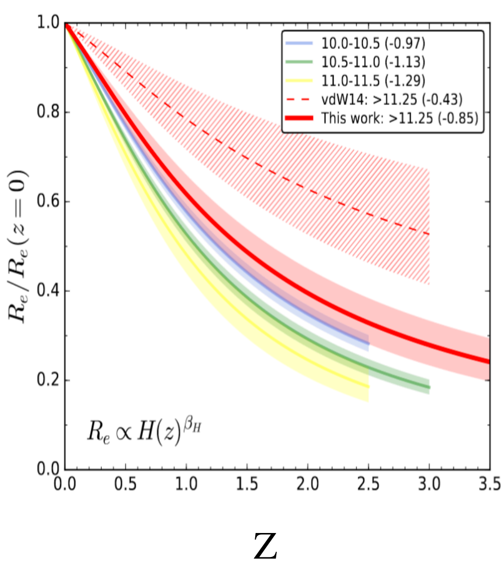
(ii) Another track dominated by (mainly dry) mergers,

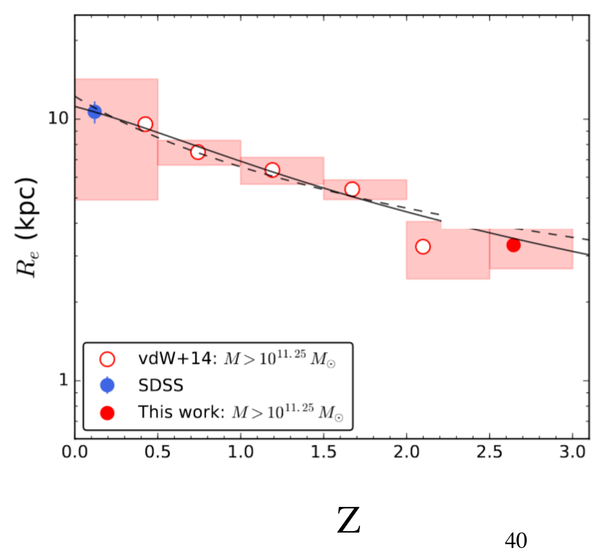
where their size increase proportionally to their mass.

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

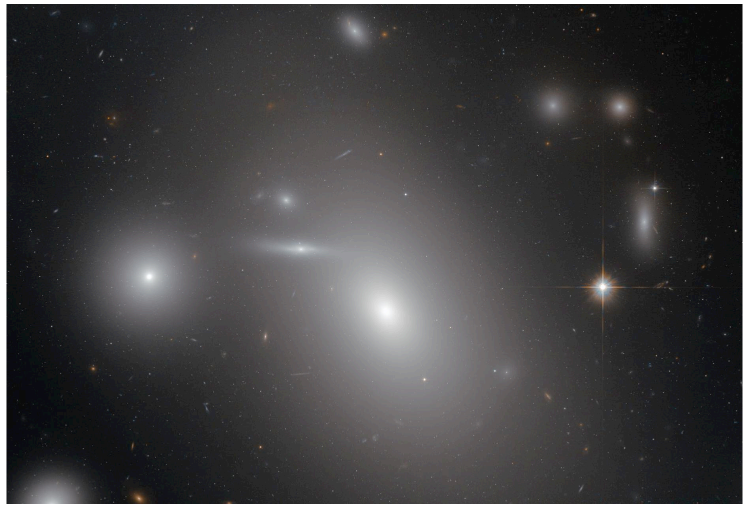
- Half light radii for $M \geq 10^{11.25} M_{\odot}$ vs redshift (Patel et al 2017)
- Elliptical Galaxies grow in size over cosmic time
- Rate at which they grow depends on mass- more massive ones at early times grow slower.

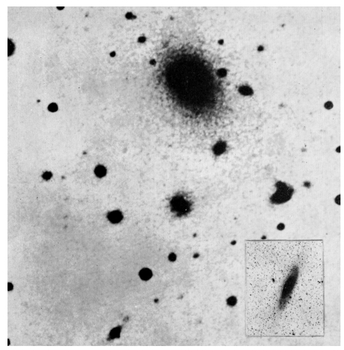




Special Objects- The most massive systems

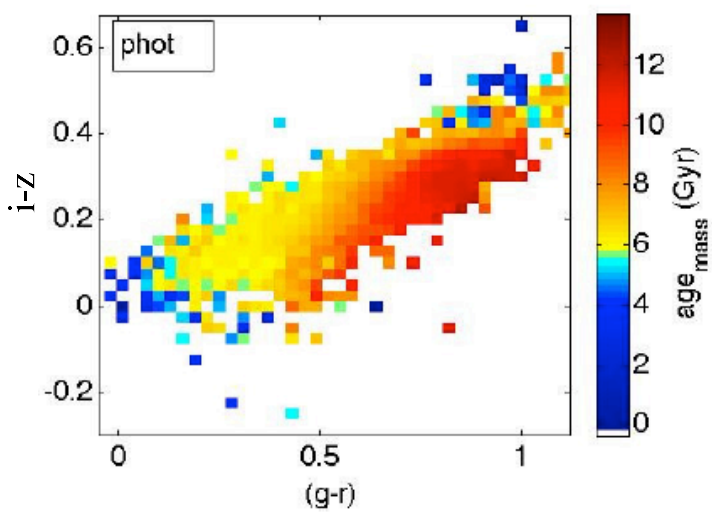
- 'cD' (central dominant) galaxies lie only at the centers of groups and clusters- not all brightest cluster galaxies (BCGs) are cDs.
- Their surface brightness profiles are very extended and they often have very rich populations of globular clusters. Quite spheroidal shape.
- X-ray emission in clusters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

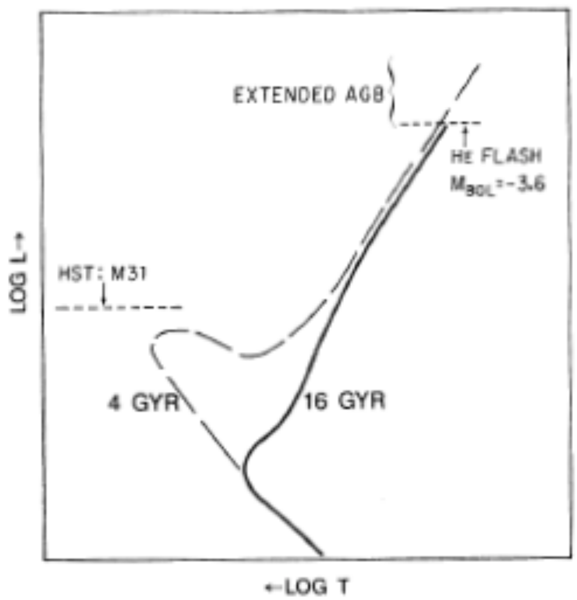


Color-color plot
Graves et al 2011

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

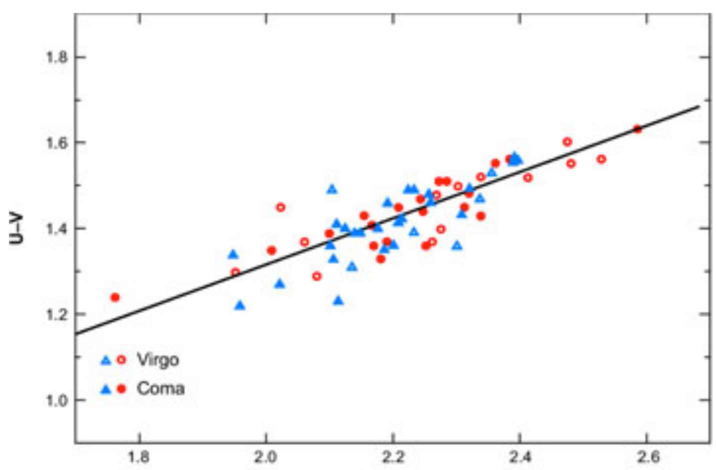
Problem in Getting Ages

- 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

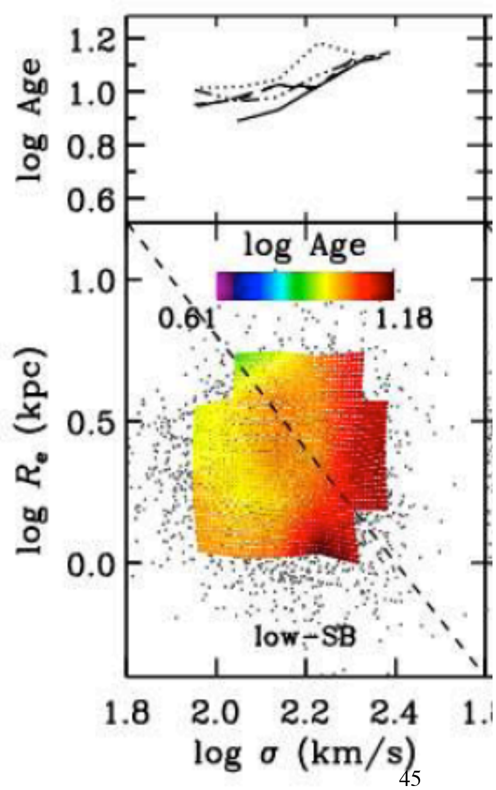


log σ

Bower, Lucy, Ellis 1991

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...



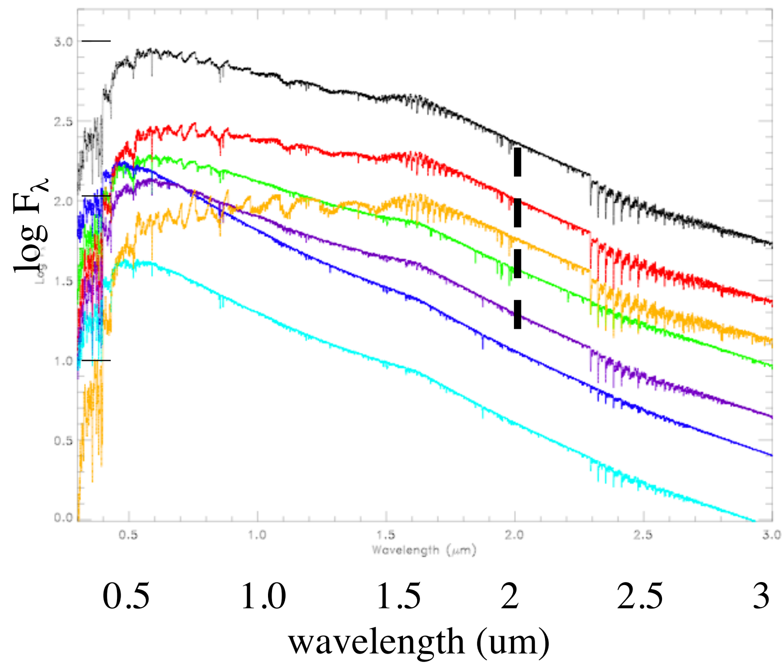
- lines of constant age run nearly vertically, indicating that stellar population age is independent of R_e (scale length in Sersic fit) at fixed σ (stellar velocity dispersion.

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

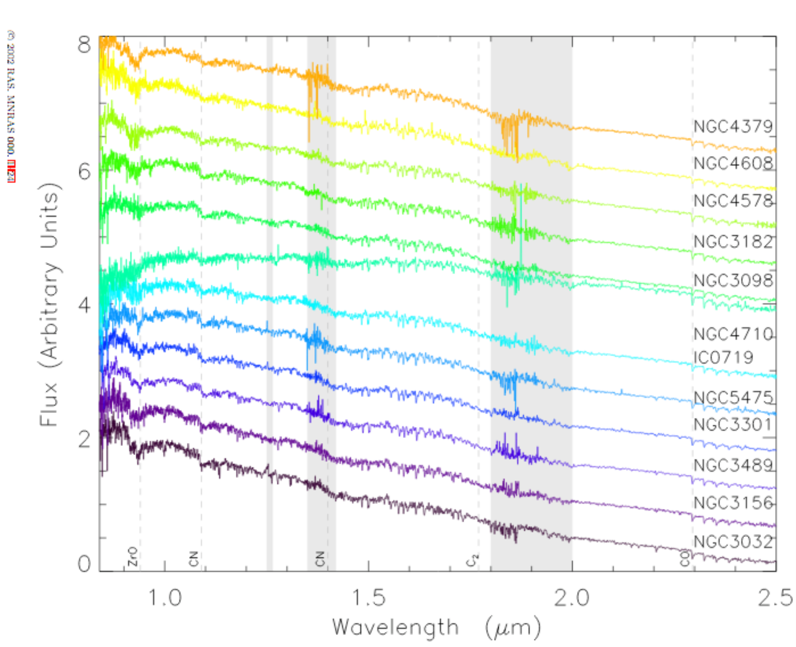
Synthetic Spectum of 16Gyr SSP- Kroupa IMF

- 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



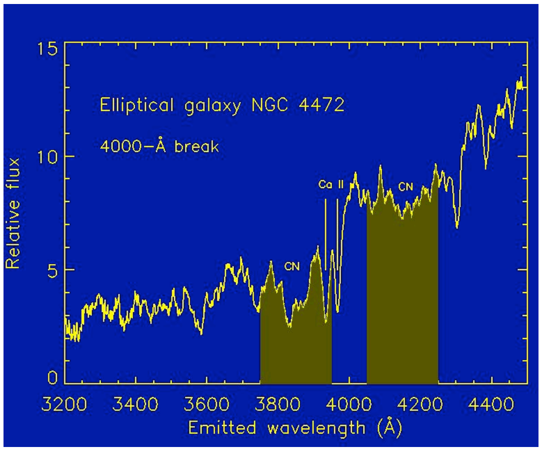
Spectra of Ellipticals

- IR spectra....

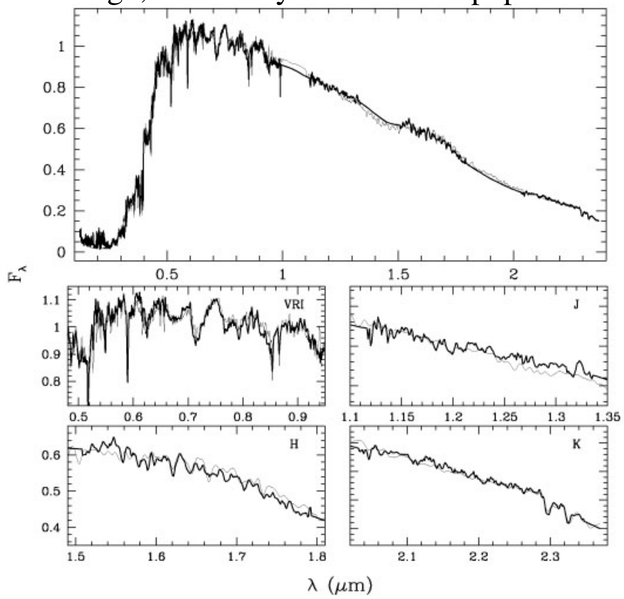


Spectrum of Ellipticals

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



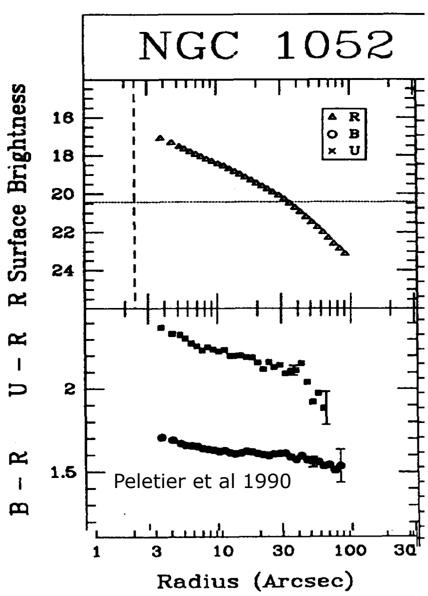
'standard' optical colors UBVRI are not very sensitive to age, metallicity of old stellar pops



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

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)

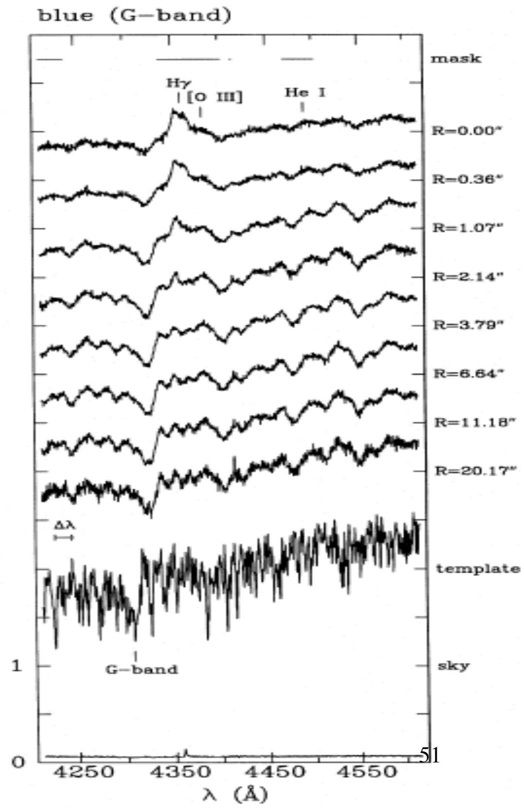


Because of the color-age degeneracy its not clear what causes the color gradients <u>without spectra</u>

Analysis of Spectral Data

- fit for a width and shift-(the shift is due to both the Hubble velocity and galaxy velocity structure) 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



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.

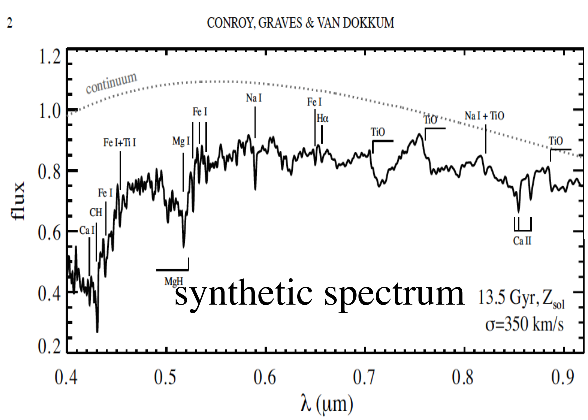


Figure 1. Model spectrum for an age of 13 Gyr and solar metallicity. The spectrum has been smoothed with a velocity dispersion of $\sigma = 350\ \mathrm{km\,s^{-1}}$, equal to the smoothing applied to the early-type galaxy data analyzed in this paper. Strong features are labeled. Also included is the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

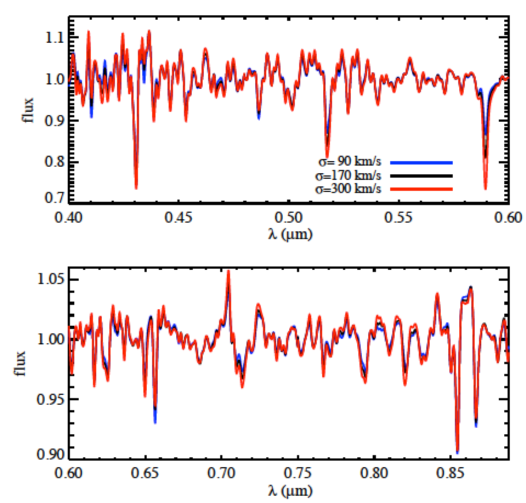
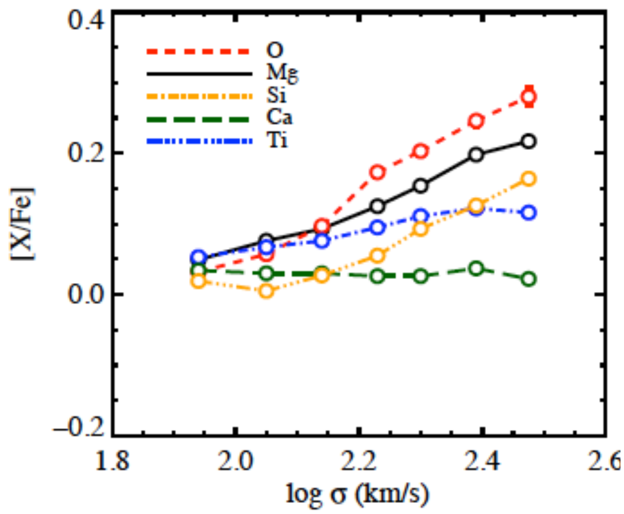


Figure 7. Continuum-normalized stacked spectra of SDSS early-type galaxies in three velocity dispersion bins.

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

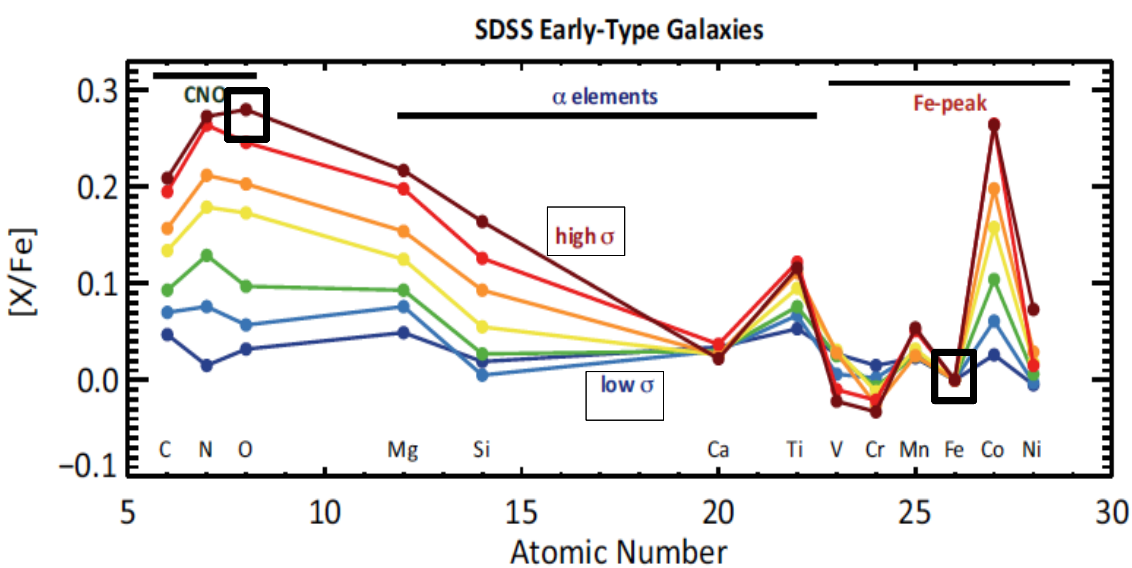
Metallicity

- 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

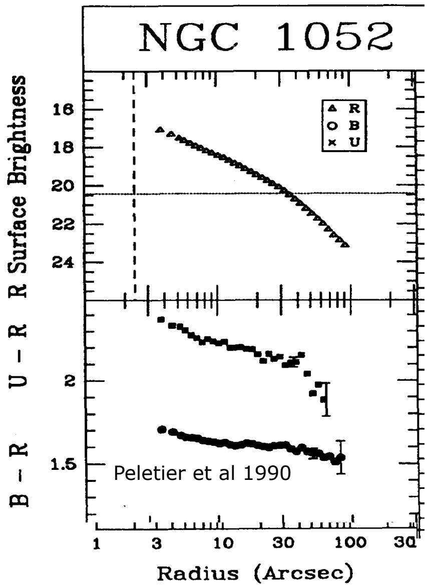
Patterns from Spectroscopy



Conroy et al 2013

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>

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

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; many of the *least massive galaxies* continue to form stars until present, while the *most massive galaxies* stopped forming stars at an early epoch