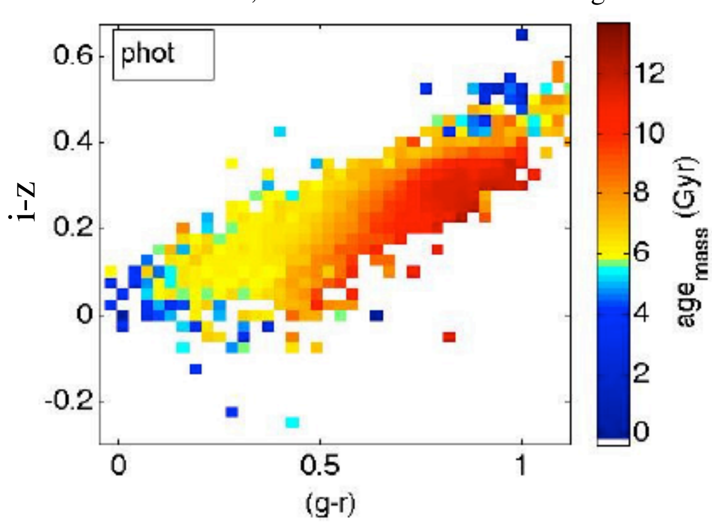
Elliptical Galaxies So Far

- 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 !**

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, somewhat less sensitive to age.

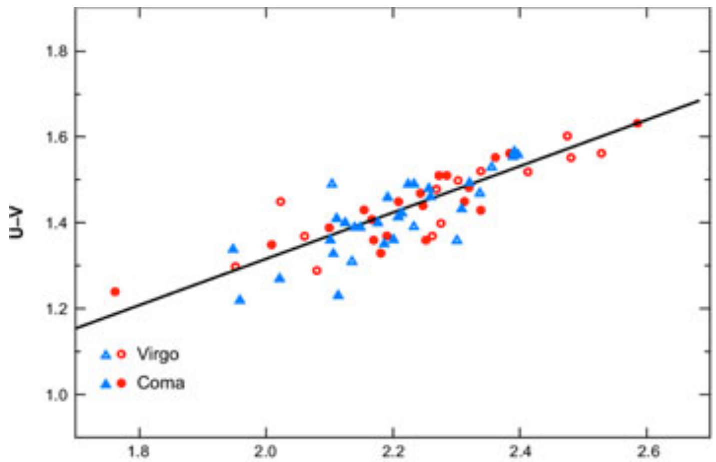


Color-color plot
Graves et al 2010

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 theorem), but leaves colors unchanged,

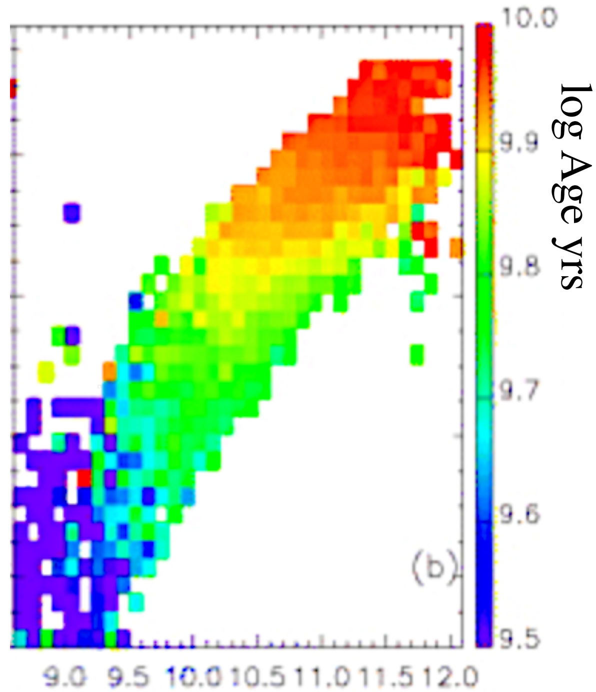


log σ

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)



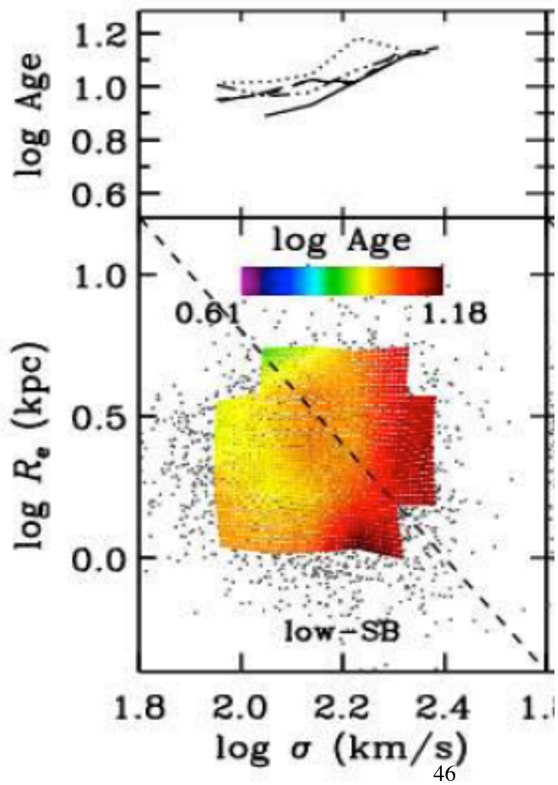
log M/M$_\odot$

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

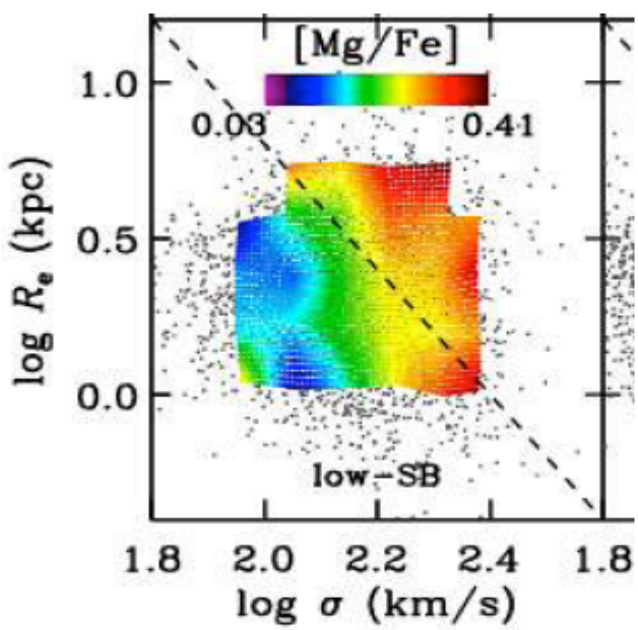
Strong connection of chemical composition structural parameters, mass, age...
Strong clues to how stars/ galaxy form...

- lines of constant age run nearly vertically, indicating that stellar population age is independent of R_e (scale length in Sersic fit) 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?

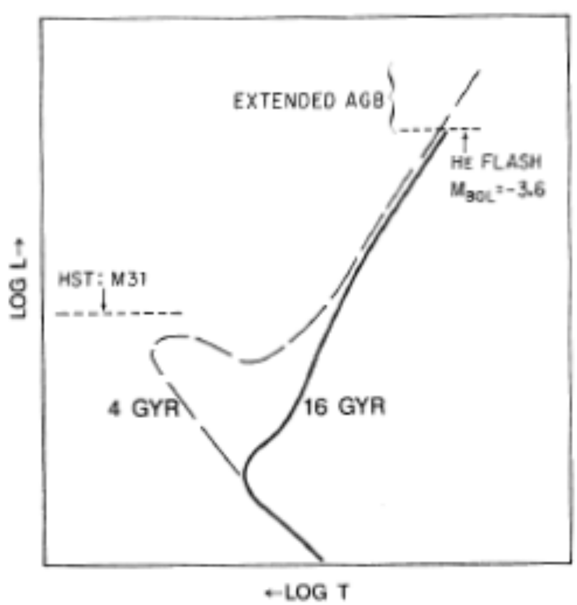


Optical Spectra

- 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

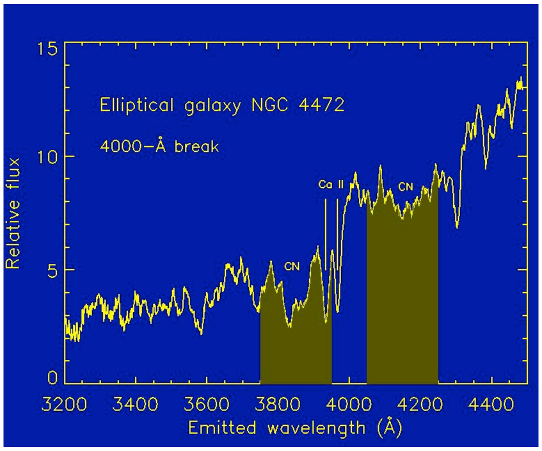
- The problem is that most of the stellar light is from giants but most of the mass is on the Main Sequence
- On the giant branch there is not much difference between 4 and 16Gyr aged populations

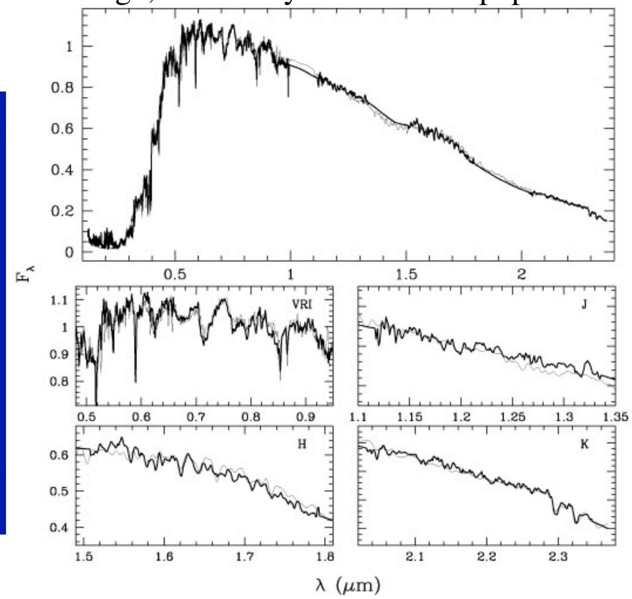


Spectrum of Ellipticals

- 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

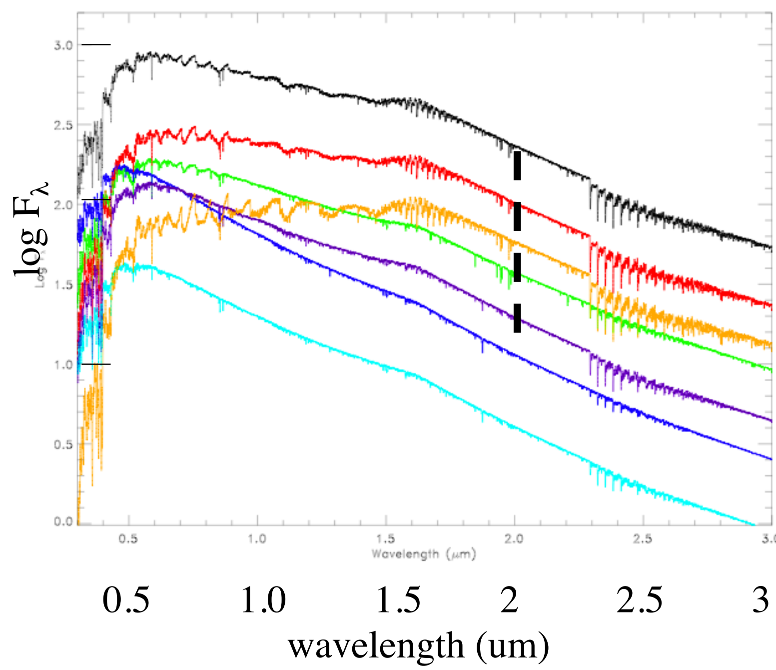




see GuyWorthy's web page http://astro.wsu.edu/worthey/dial/dial_a_model.html

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**

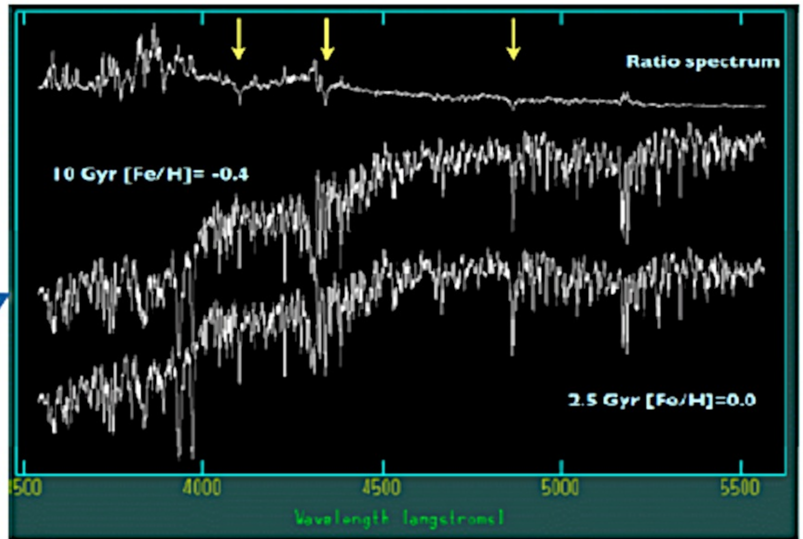


Age Metallicity Degeneracy

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

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

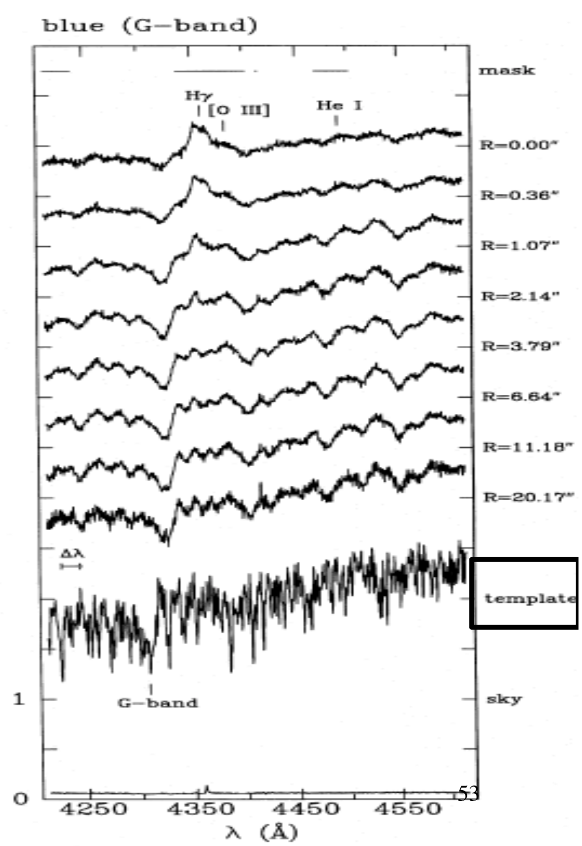


Vazdekis et al. (2007) models from MILES library

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/dispersion.
- 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. Now possible for single objects with MUSE

2 CONROY, GRAVES & VAN DOKKUM

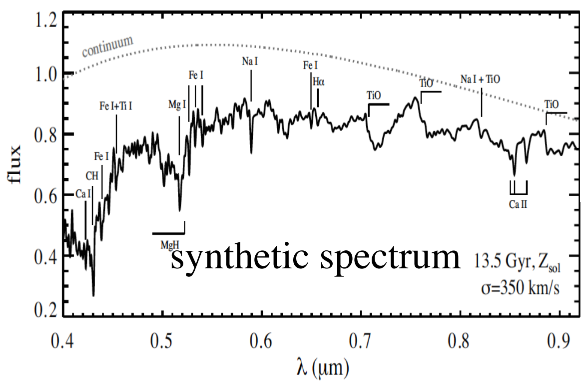


Figure 1. Model spectrum for an age of 13 Gyr and solar metallicity. The spectrum has been smoothed with a velocity dispersion of $\sigma = 350$ km s^{-1}, equal to the smoothing applied to the early-type galaxy data analyzed in this paper. Strong features are labeled. Also included is the location of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

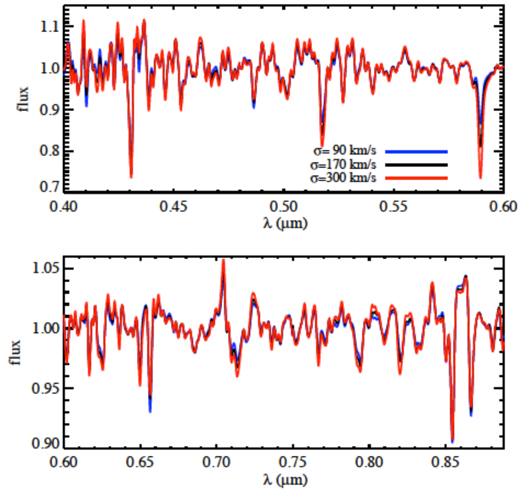
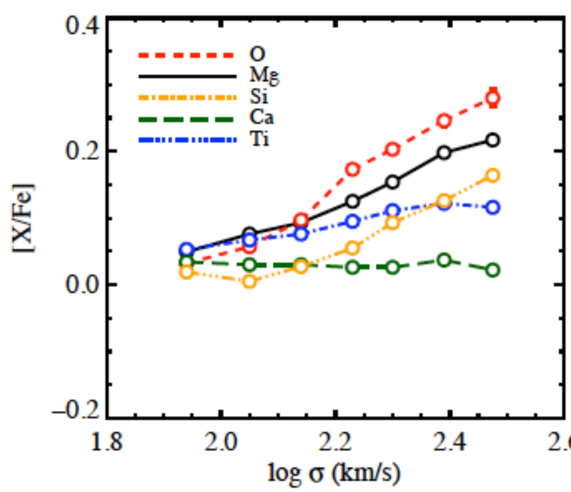


Figure 7. Continuum-normalized stacked spectra of SDSS early-type galaxies in three velocity dispersion bins.

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

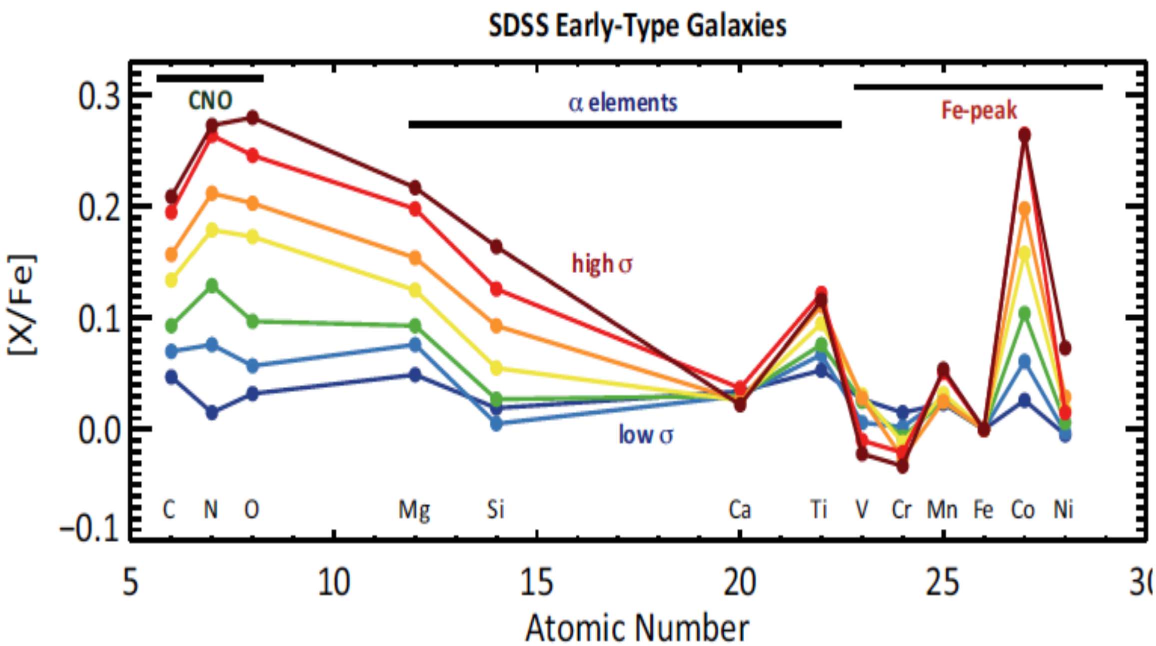
Metallicity

- 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



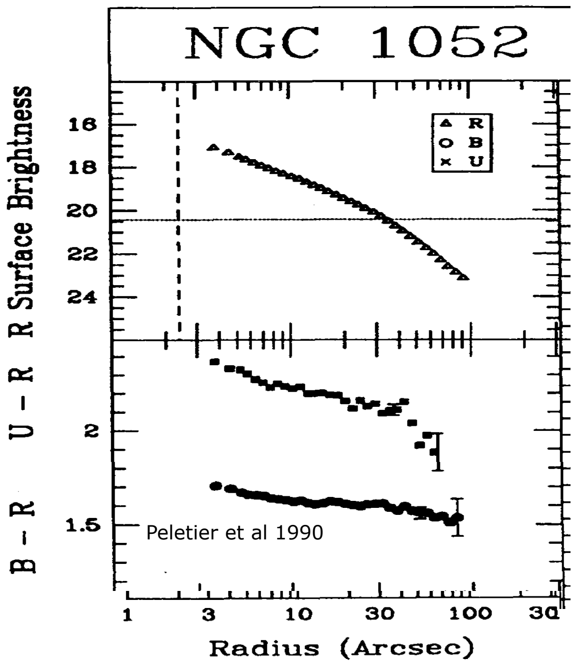
Conroy et al 2014

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 E galaxies become bluer outward- mostly due to decreasing metallicity



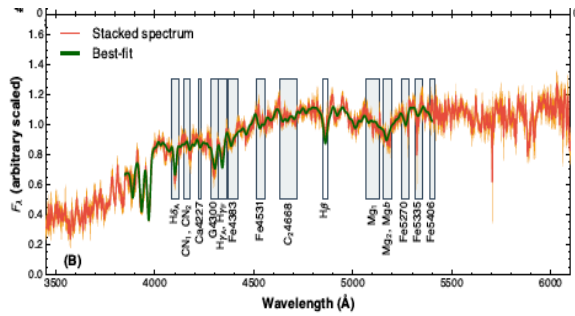
Because of the color-age degeneracy its not clear what causes the color gradients without spectra 58

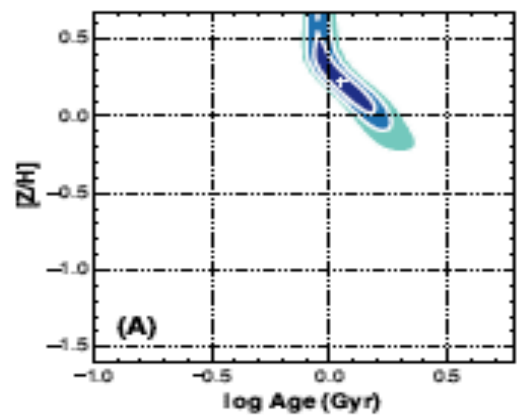
Summary of Abundance Data

- 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* form stars for longer times, while the *most massive galaxies* stopped forming stars at an early epoch

What About at Higher Redshift

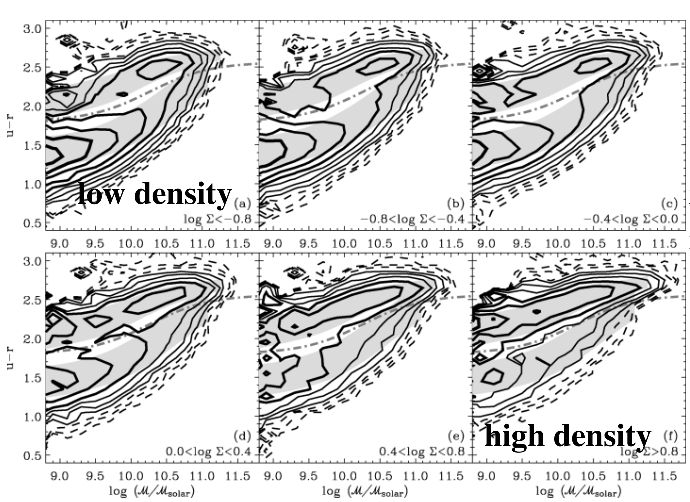
- Ondera et al 2015ApJ...808..161 have studied massive quenched galaxies at 1.25< z< 2.09
- They find that these quenched galaxies if evolved passively to z = 0, would have stellar population properties in excellent agreement with local counterparts at similar stellar velocity dispersions, which qualifies 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





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

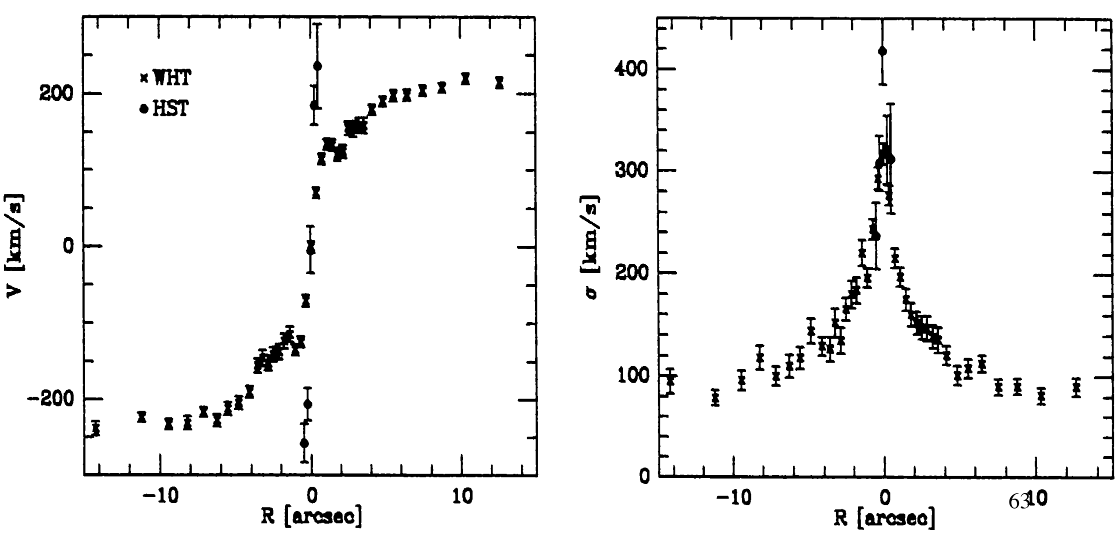
  in the densest place in the universe, rich clusters of galaxies physical processes occur (e.g. ram pressure stripping, galaxy harassment) that tend to destroy spirals. - BUT if ellipticals are primarily formed by mergers, this cannot happen in massive clusters since the galaxies are moving too fast to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

Kinematics

- Examples of 2 galaxies M87 and NGC 4342
  - one with no rotation and the other with lots of rotation
- The other parameter is velocity dispersion- the width of a gaussian fit to the velocity

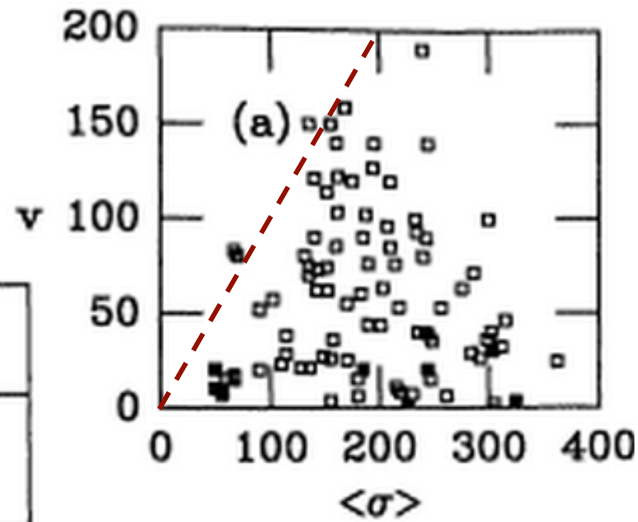
NGC4342
van den Bosch

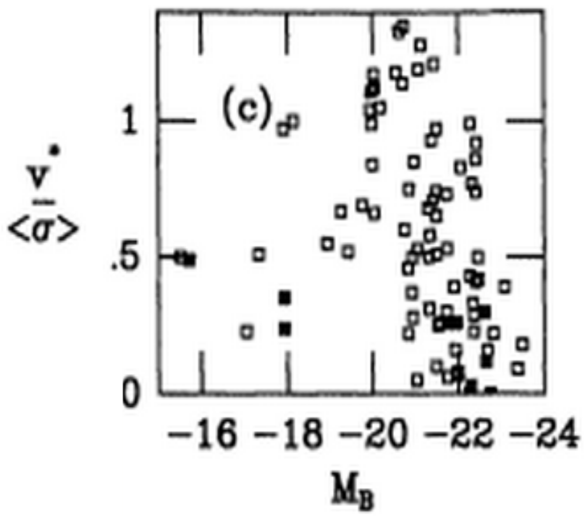
its flattening is consistent with rotation



Massive Ellipticals Rotate Slowly if at ALL

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



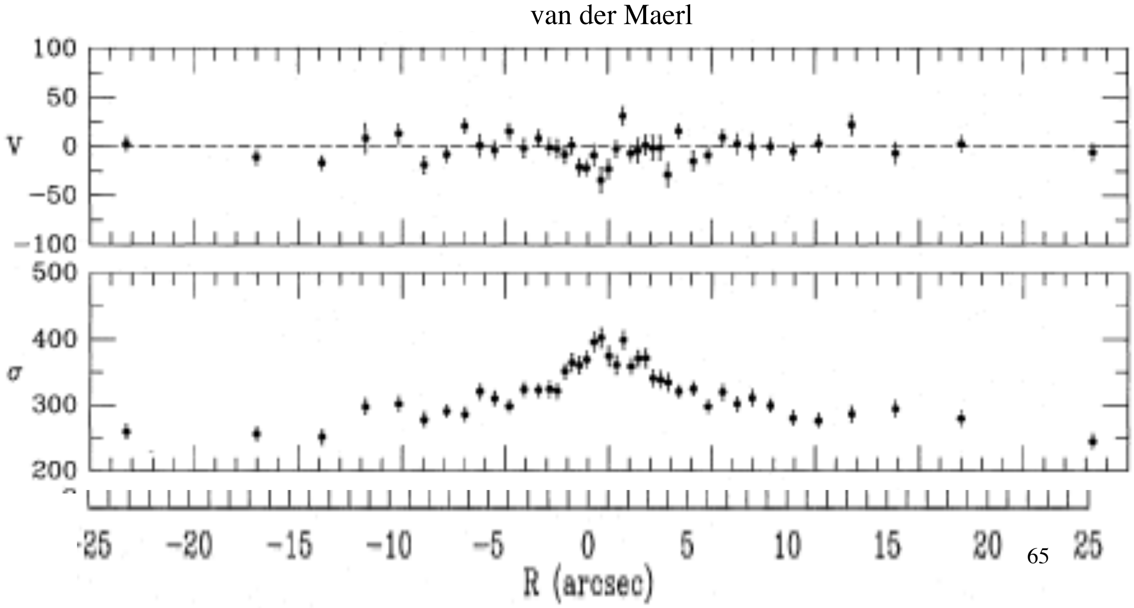


de Zeeuw and Franx 1991

Kinematics

- Kinematics- the features used to measure the velocity field are due to stellar absorption lines: however these are 'blurred' by projection and the high velocity dispersion of the objects.
- Spatially resolved spectra help...

M87- No Rotation
van der Maerl



Summary So Far

- Fundamental plane connects luminosity, scale length, surface brightness, stellar dynamics and chemical composition
  - - Faber Jackson relation L ~ σ^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

Kinematics

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

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

Observables:

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

of the "dynamical" mass.

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

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

…

H Rix

Dynamics of Ellipticals

- More complex than spirals- 3D system (1 velocity and 2 position degrees of freedom can be measured).
- The prime goal of dynamical measurements is to determine the mass of the system as a function of position (mostly radius) and the mass-light ratio of the stars. Unfortunately the data are not directly invertable and thus one must resort to models and fit them.
- Most recent models have been motivated by analytic fits to detailed dark matter simulations derived from large scale cosmological simulations.
- Additional information has been provided by
  - gravitational lensing (only 1 in 1000 galaxies and distant),
  - velocity field of globular clusters
  - use of x-ray hot gas halos which helps break much of the degeneracies.
  - Hot gas and globular velocities can only be measured for nearby galaxies (D<40Mpc) and only very massive galaxies have a measurable lensing signal.

Mass Determination

- for a perfectly spherical system one can write the **Jeans equation** as
- $(1/\rho)d(\rho<v_r>^2)/dr+2\beta/r<v_r>^2=-d\phi/dr$

  where ϕ is the potential and β is the anisotropy factor $\beta=1-<v_\theta>^2/<v_r>^2$
- since $d\phi/dr=GM_{tot}(r)/r^2$
- Mass is $M_{tot}(r)=r/G<v_r>^2$ $[d\ln\rho/d\ln r+d\ln/<v_r>^2/d\ln r+2\beta]$

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

- Notice the nasty terms
- V_r is the rotation velocity σ_r $\sigma_{\theta,}$ σ_ϕ are the 3-D components of the velocity dispersion ν is the density of mass (usually we use stars as the tracer of mass)
- All of these variables are 3-D; we observe projected quantities !
- The analysis is done by generating a set of stellar orbits and then minimizing
- Rotation and random motions (dispersion) are both important.

Jeans Eq

- V is the rotation velocity and the radial (σ_r) and $\sigma_{\theta,}$, σ_ϕ are the angular components of the velocity dispersion

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

Mass Determination

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

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

re-write this as $M(R)=-(<v_r^2>r/G)[dln/dlnr+dlnv_r^2/dlnr+2\beta]$

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

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

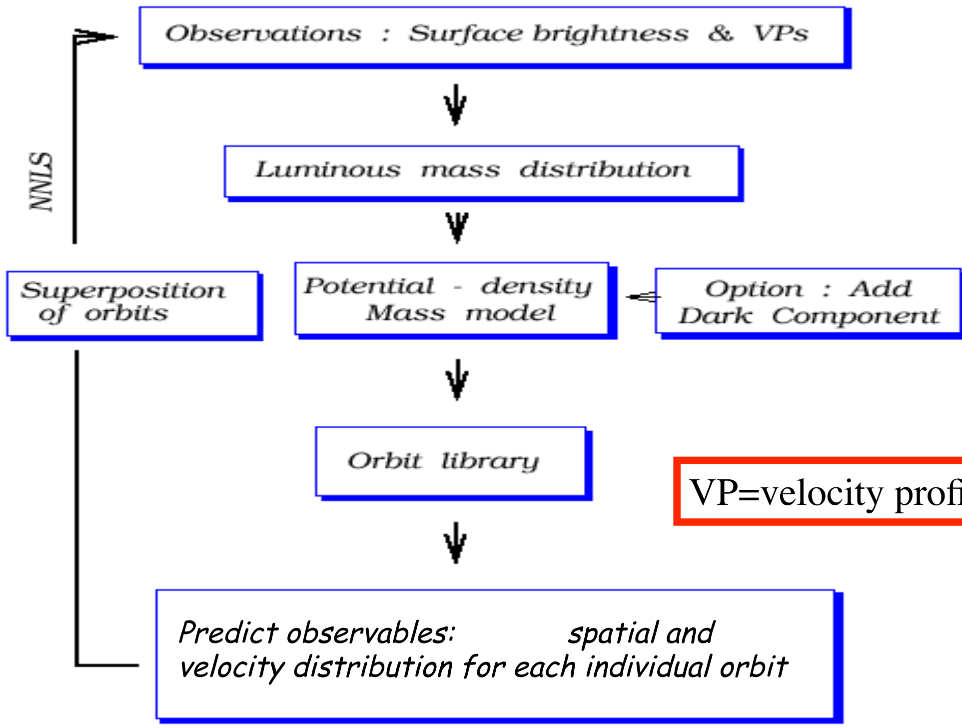
Schwarschild Orbit-Superposition Models

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

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

Modeling

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



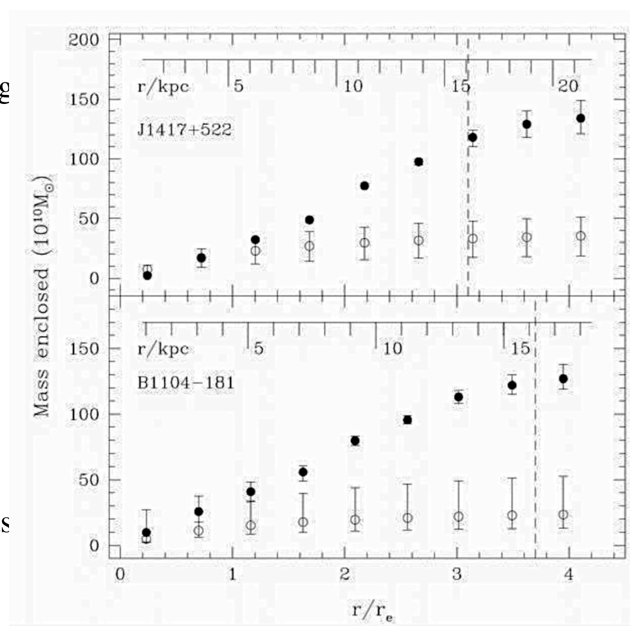
VP=velocity profiles

Degeneracies

- degeneracies inherent in interpreting projected data in terms of a three-dimensional mass distribution for pressure-supported systems.
- Chief among these degeneracies is that between the total mass-density profile and the anisotropy of the pressure tensor

Results

- The dark matter fraction increase as one goes to large scales and with total mass
- Density profile is almost isothermal
- d log ρ_{tot}/d log r ~r^{-2} which corresponds to a flat circular velocity profile



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

Ferreras , Saha , and . Williams 2005

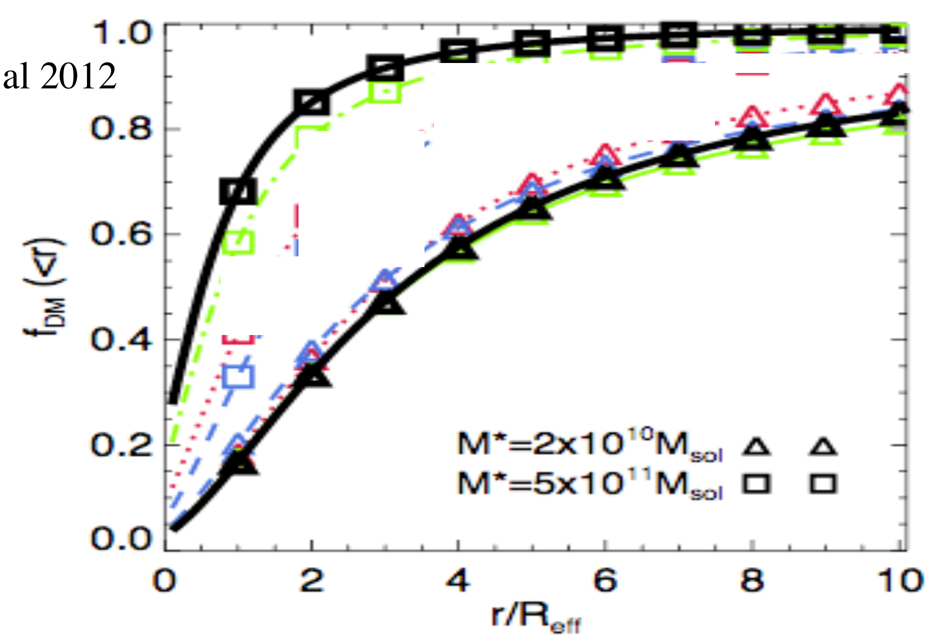
Mass Determination

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

Dark Matter Out to 5R_e

General result: DM fraction increases as R_e, σ, n and M* increase, but the DM density decreases as R_e, n and M* increase

Deason et al 2012

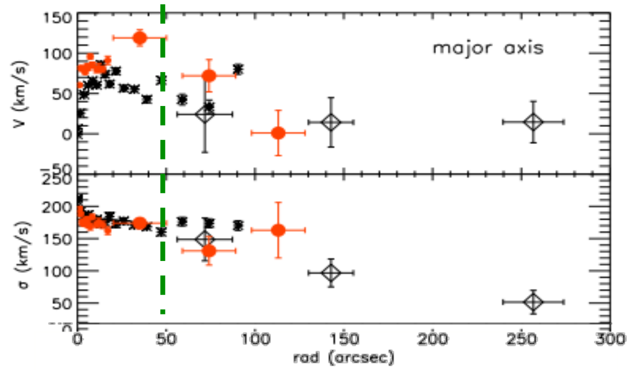


Detailed Fit for only a Few Objects at Large Radii

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

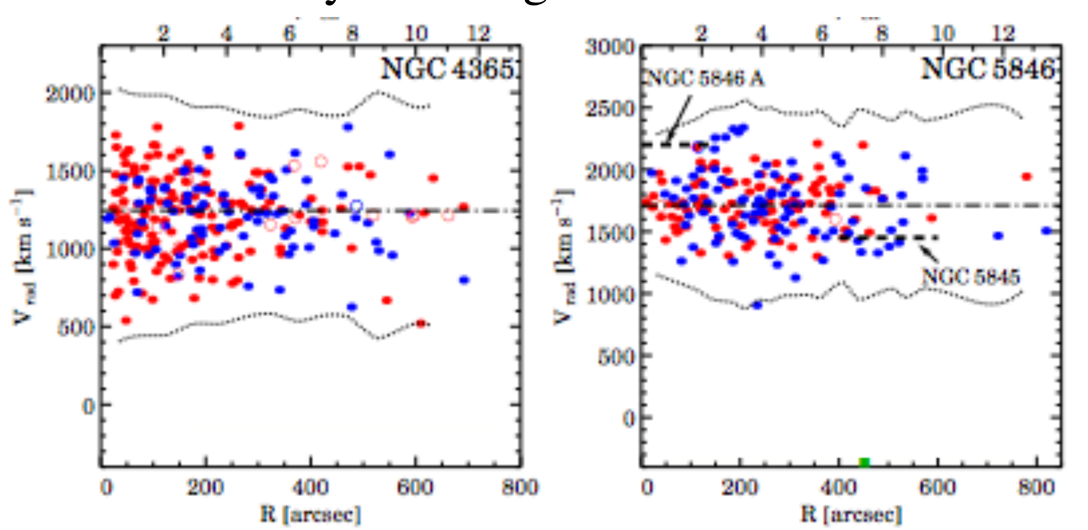
However the shape of the potential is not well determined

R_e

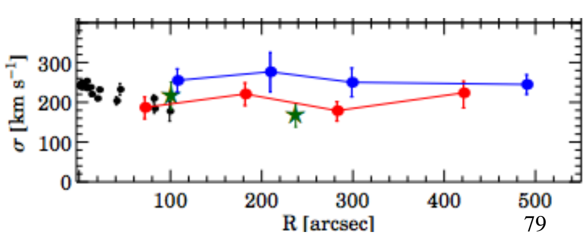


Weijmans et al 2010

Velocity field of globular clusters



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



X-ray Emission

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

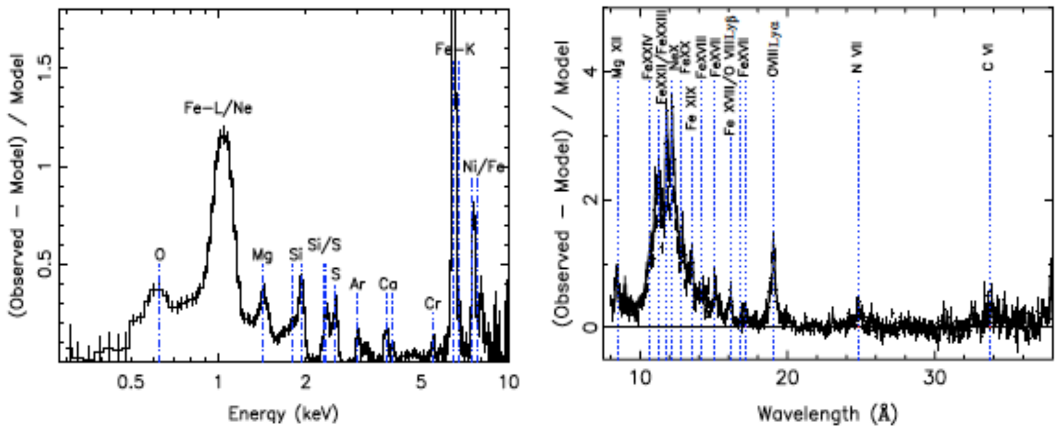


Fig. 31 *Left panel* The line spectrum of the cluster 2A 0335+096, as observed with *XMM-Newton* EPIC

Use of X-rays to Determine Mass

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

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

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

gives for for a spherically symmetric system

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

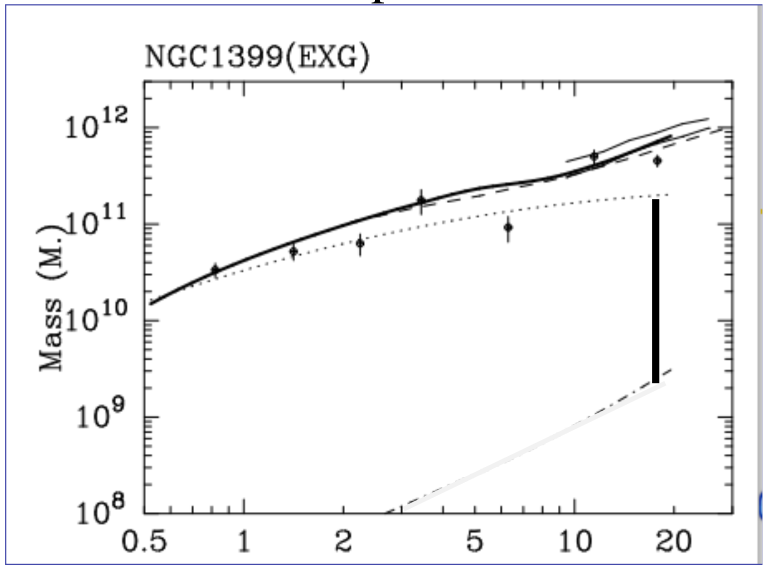
With a little algebra and the definition of pressure - the total cluster mass (dark and baryonic) can be expressed as

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

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

NGC1399- A Giant Elliptical

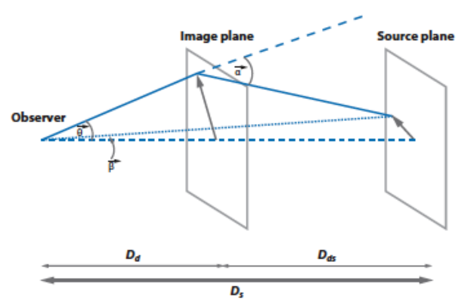
- Solid line is total mass
- dotted is stellar mass
- dash-gas mass is gas
- In central regions gas mass is ~1/500 of stellar mass but rises to 0.01 at larger radii
- Gas extends beyond stars (like HI in spirals)



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

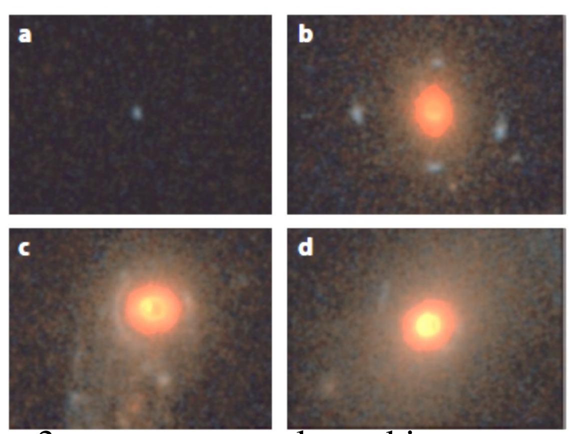
Lensing- Breaks Degeneracies

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



- dynamical models provide masses enclosed within a *spherical* radius, while strong lensing measures the mass inside a *cylinder* with axis parallel to the line-of-sight
- Einstein radius $\theta_e=4\pi(\sigma_{sis}/c)^2 D_{ls}/D_s$

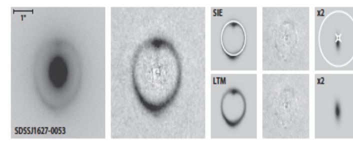
  $=(\sigma_{sis}/186 \text{ km s })^2 D_{ls}/D_s$arcsec for a isothermal sphere
- where, σ_{sis} is the velocity dispersion of a simple isothermal potential D_{ls} is the distance from lens to source and D_s is the distance from observer to source



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

- Remember that the density of an isothermal sphere is $\rho(r)=\sigma^2_{sis}/2\pi G r^2$
- See 2015MNRAS.452.2434S
  Spiniello, C et al The X-Shooter Lens Survey - II. Sample presentation and spatially-resolved kinematics and

Disentangle the dark and luminous mass components by combining lensing and extended kinematics data sets, and we are also able to precisely constrain stellar mass-to-ligh ratios and infer the value of the low-mass cut-off of the initial mass functions (IMF), by adding spectroscopic stellar population information.



- Surprising result that the XLENS systems have an IMF slope steeper than Milky Way-like

Dark Matter in Ellipticals

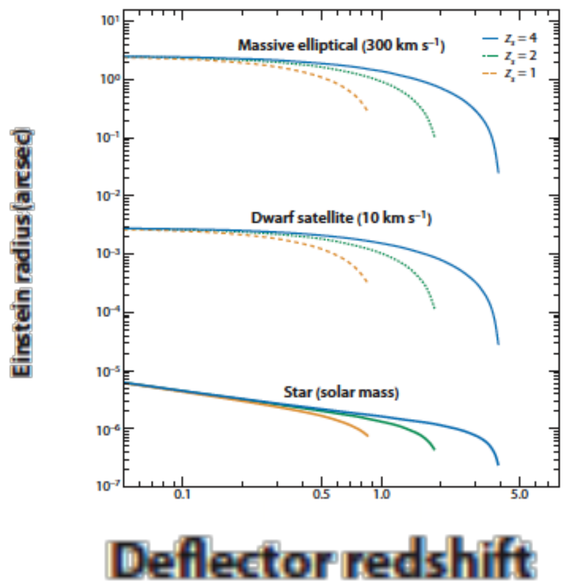
- It is rather difficult to determine whether dark matter is important in the central regions of ellipticals with just velocity and surface brightness data- lensing breaks the degeneracies

Why Giant Ellipticals as Lenses

- To first order strong lensing is only sensitive to the mass enclosed by the *Einstein radius*

which occurs at the critical surface density $\Sigma = c^2 D_s / (4\pi G D_d D_{ds})$

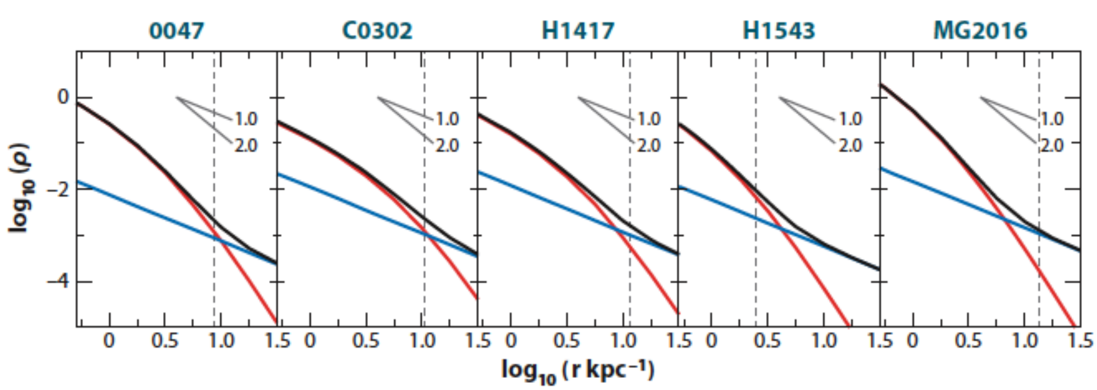
- Ellipticals Einstein radii are ~2" over a wide range of redshifts - but only 1/1000 galaxies are strong lenses
- cross section (Einstein radius²) goes as σ^4. Ellipticals tend to have higher σ



Treu 2010 Annu. Rev. Astron. Astrophys. 2010. 48:87

Mass Profiles From Lensing + Photometry

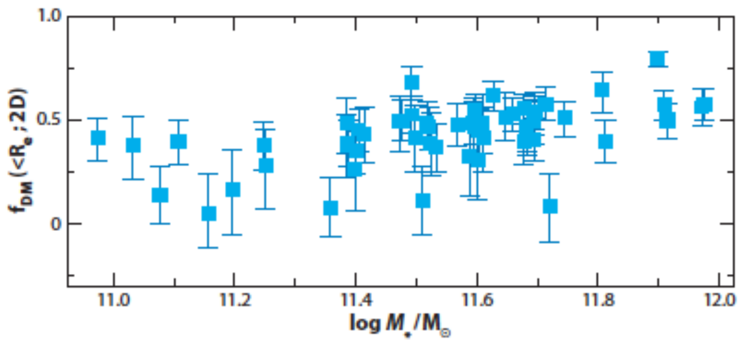
- Blue is mass density of dark matter, red that of stars for 4 galaxies (Treu 2010) as a function of radius (vertical line is Einstein radius)
- Dark dominates in all of these at large radii
- While neither stars nor DM have a power law distribution in density the sum does-similar to the disk-halo conspiracy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



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

Average Dark Matter

- Treu (2010) shows that at r~R_e ~40% of the mass is dark, roughly independent of mass
- If we model the mass distribution as $d \log \rho_{tot}/d \log r$=-γ we find that γ ~2 fits most objects ((Koopmans et al. 2009b).
- The small scatter around γ= 2 is remarkable considering that neither the DM halo nor the stellar mass are well described by a simple power-law profile. Nevertheless, the two components add up to an isothermal profile



Detailed Analysis

- Sonnenfeld et al show that γ is roughly constant with redshift and mass
- Also directly show distribution of baryons (stars) is different from total matter

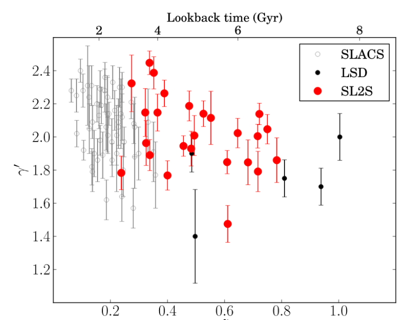
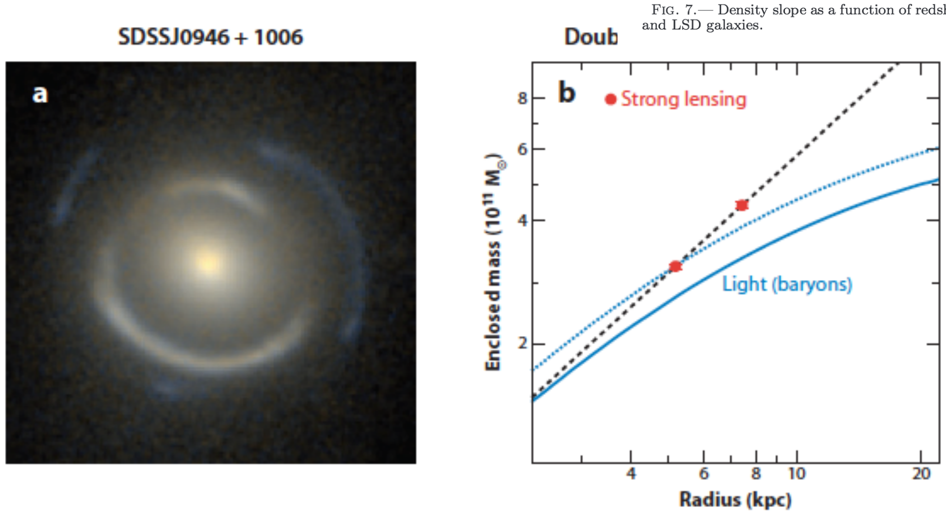


FIG. 7.— Density slope as a function of redshift for SL2S, SLACS and LSD galaxies.



The Big Picture of Elliptical Galaxy Formation

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

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

Growth of Stellar Mass Across Cosmic Time

- Assumes a Saltpeter IMF Finkelstein 2015 arxiv1511.05558
- The massive ellipticals 'stopped' growing at z~2 when ~30% of all stellar mass had formed

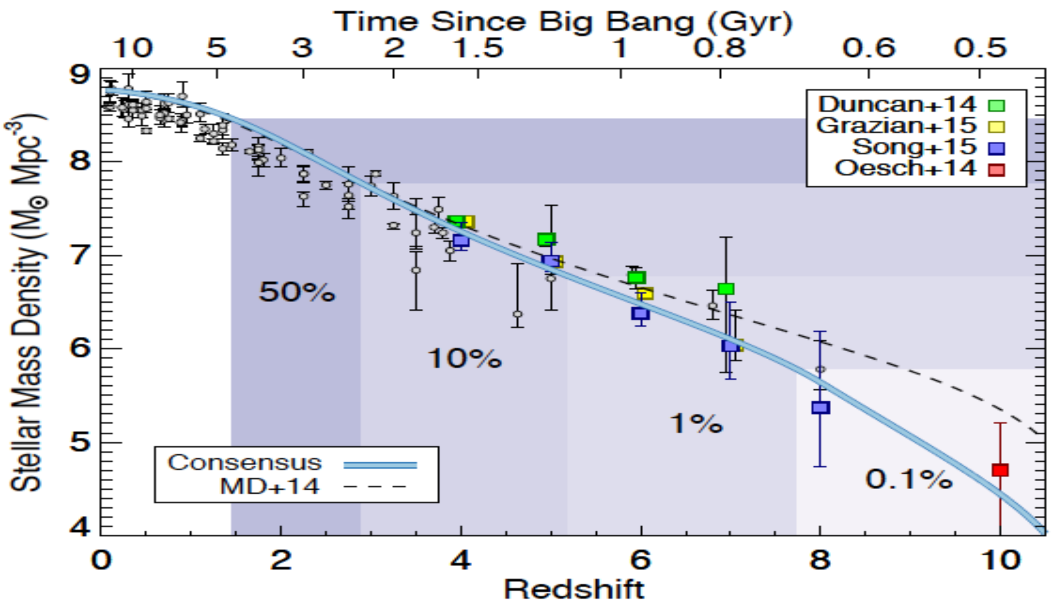
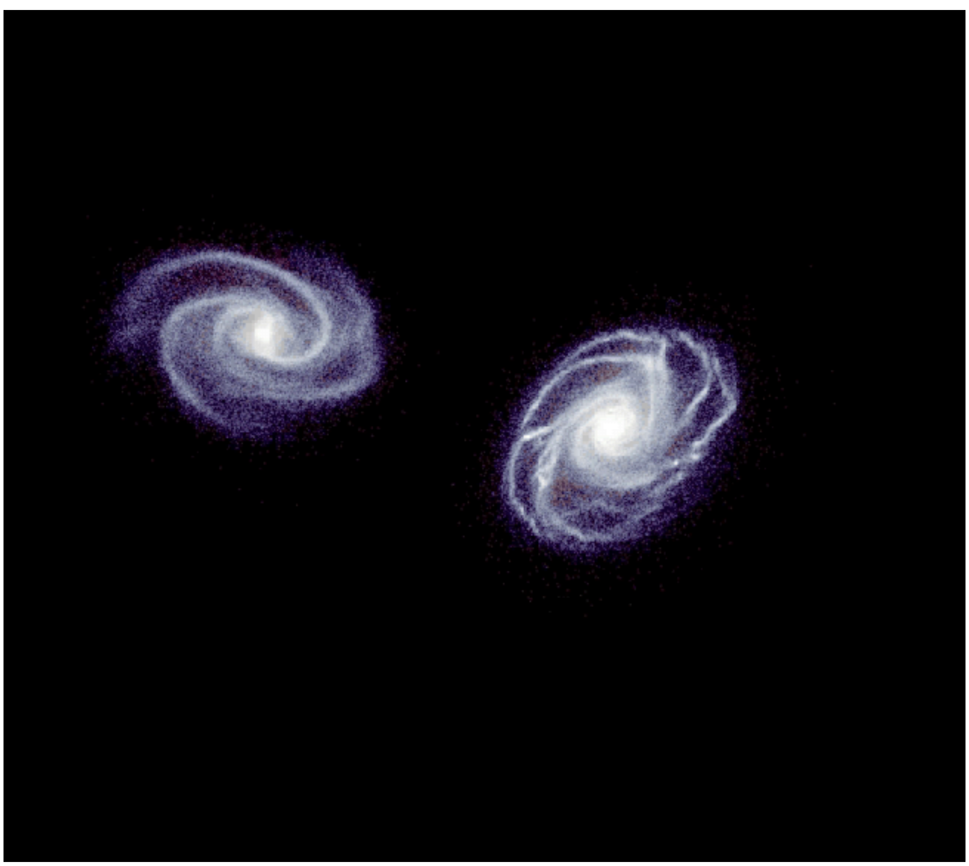
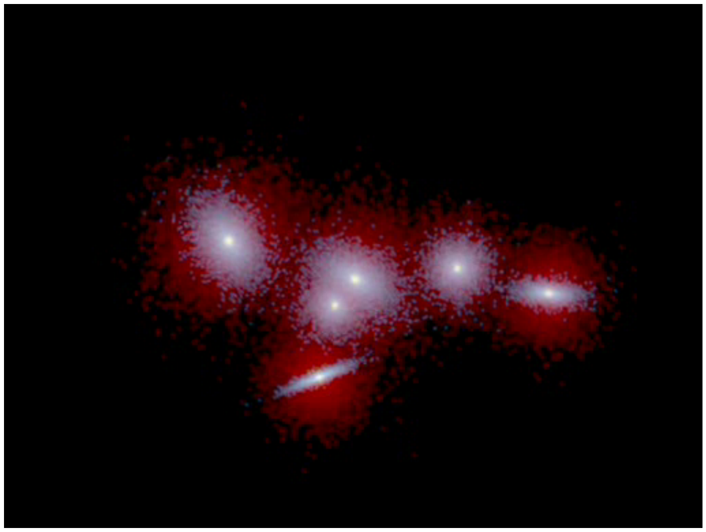


Figure 8. The evolution of the total stellar mass density in the universe, all derived assuming a Salpeter IMF. The low redshift



Computer simulation of galaxy collisions that make a big elliptical



J. Barnes, UH