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, $L \sim \sigma^4$
- – 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

Physics of Fundamental Plane (M. Whittle)

$< I_e > \; = \; ½ \, L_{tot} / \pi \, R_e^2$

$M/R_e \; = \; c\sigma_e^2$ (virial equilibrium)

- these give:

$R_e = (c/2\pi)\,(M/L)^{-1}\sigma_e^2 \; < I_e >^{-1}$ or equivalently,

$\text{Log } R_e = \text{Log } [(c/2\pi)\,(M/L)^{-1}] + 2 \text{ Log}\sigma_e - \text{ Log} <$ $Ie >$ or

$\text{Log } R_e = \text{Log } [(c/2\pi))\,(M/L)^{-1}] + 2 \text{ Log } \sigma_e + 0.4 <$ $\mu_e >$ (since $< \mu_e > = -2.5 \text{ Log} < I_e >$)

if c and M/L are constants, then

$\text{Log } R_e = 2 \text{ Log}\sigma_e + 0.4 < \mu_e > + \text{Log}[(c/2\pi)(M/L)^{-1}]$

- Which is close to, but not quite, the F-P relation:

$\text{Log } R_e = 1.4 \text{ Log}\sigma_e + 0.36 < \mu_e >$

- To get agreement,

$(M/L) \sim M^{1/5} \sim L^{1/4}$

The F-P is rooted principally in virial equilibrium

- To first order, the M/L ratios and dynamical structures of massive ellipticals are very similar
- the populations, ages & dark matter properties are highly uniform

There is a weak trend for M/L to increase slightly with mass (× 3 across 5 magnitudes)

The narrow scatter on F-P and Mg - relations place limits on the ranges of ages and metallicities:

Ages ~ 10 - 13 Gyr; Z ~ 2-4 Z(solar)

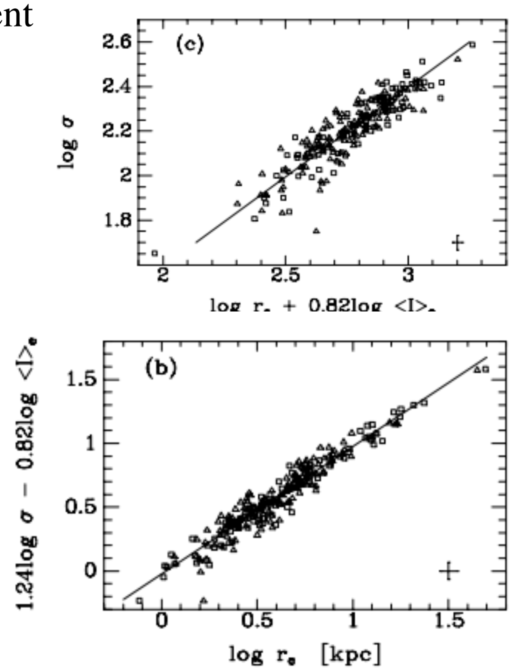
Fundamental Plane-relate their structural/dynamical status to their stellar content

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

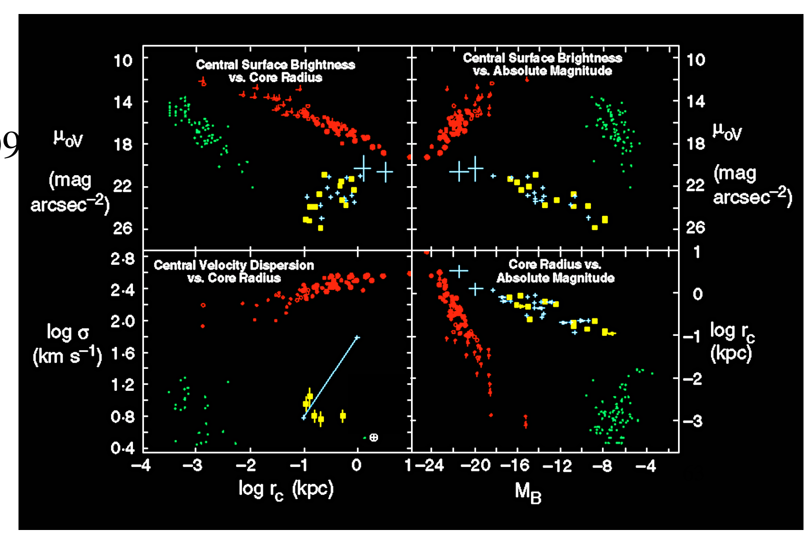
The existence of the FP implies that ellipticals

- 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).

Kormendy 2009



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

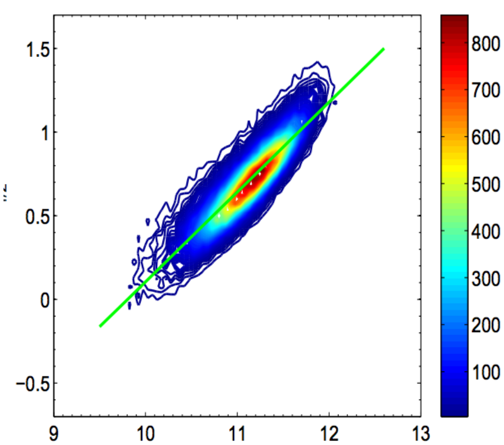
  $R_{1/2}\sim M_{stellar}{}^{1/2}$

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 $R_{1/2}$

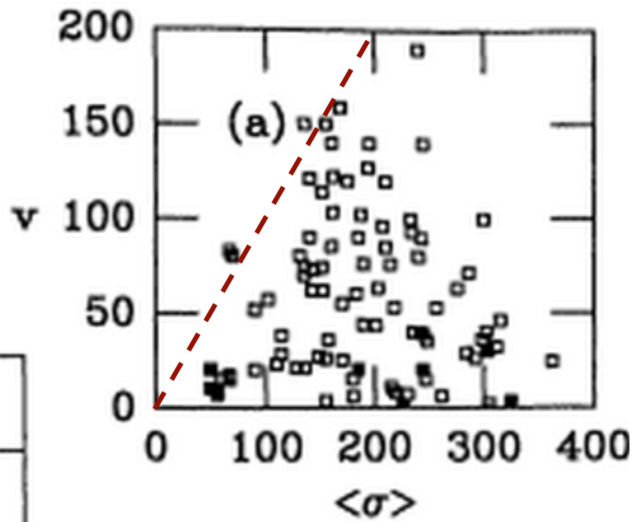


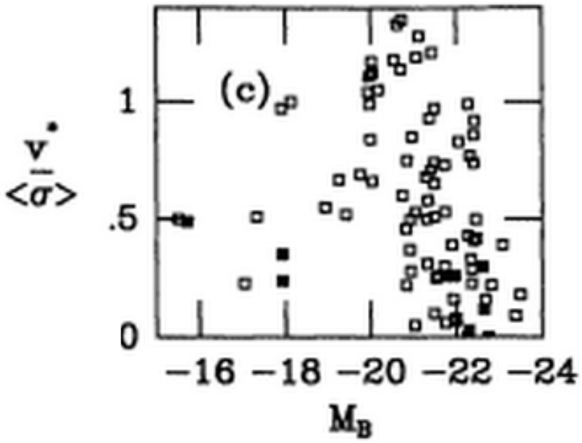
log $M_{stellar}$

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)



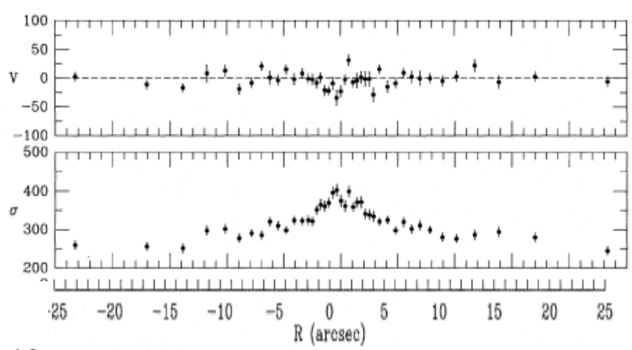


de Zeeuw and Franx 1991

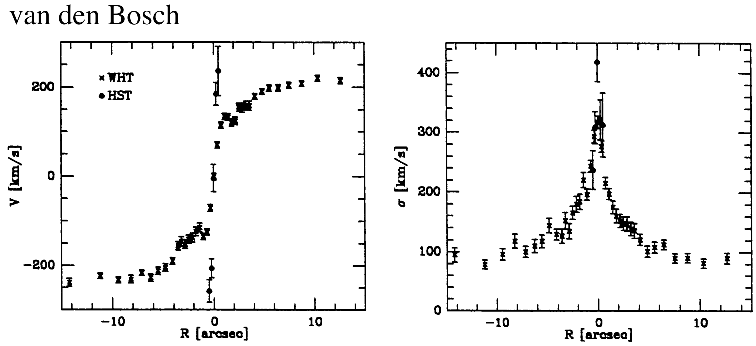
Kinematics

- 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...
- 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

M87van der Maerl



NGC4342
van den Bosch



For NGC4342 its observed flattening is consistent with rotation

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

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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

  - --
- $f(y)=I_0 e^{-y^2/2}[1+h_3H_3(y)+h_4H_4(y)]$Mon. Not. R. Astron. Soc.326, 473–489

$y=(v_{fit}-v)\sigma_{fit}$ are antisymmetric and symmetric standard Gauss – Hermite polynomials of third and fourth order and h_3 and h_4 are their coefficients, respectively; and I0 is a normalization constant

h_3 line of sight velocity dispersion asymmetry (skew)

h_4 line of sight velocity dispersion symmetric deviation from a Gausssian

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.

…

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 thus 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 $d\phi/dr=GM_{tot}(r)/r^2$
- one can write the mass as
- $M_{tot}(r)=r/G<v_r>^2$ $[d\ln\rho/d\ln r+d\ln/<v_r>^2/d\ln r+2\beta]$
- expressed in another way

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

- 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.

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Jeans Eq

- $M(R)=(V^2r/G)+(r\sigma^2_r/G)[-d\ln\rho/d\ln r-d\ln\sigma^2_r/d\ln r-(1-\sigma^2_\theta/\sigma_r^2)-(1-\sigma^2_\phi/\sigma^2_r)]$
- where V is the rotation velocity and are 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

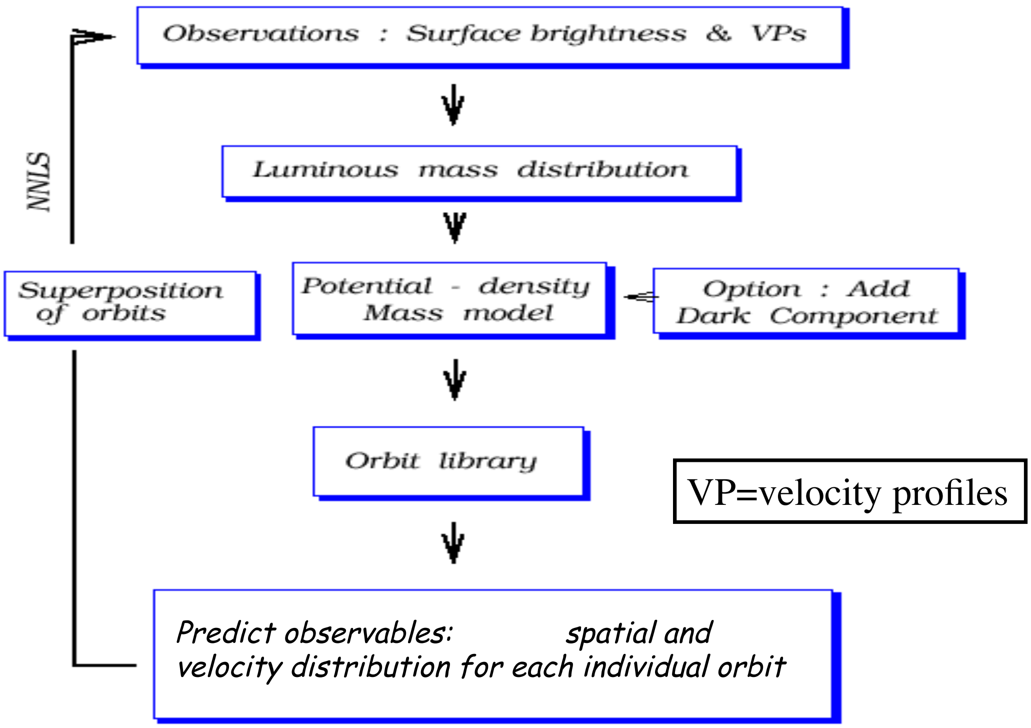
Schwarschild Orbit-Superposition Models

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

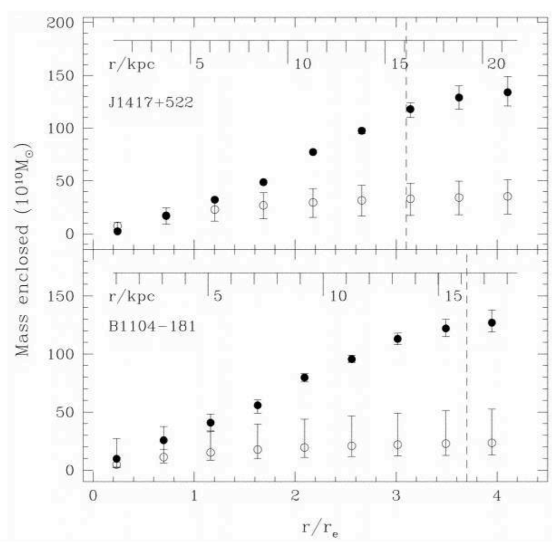


Degeneracies

- 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

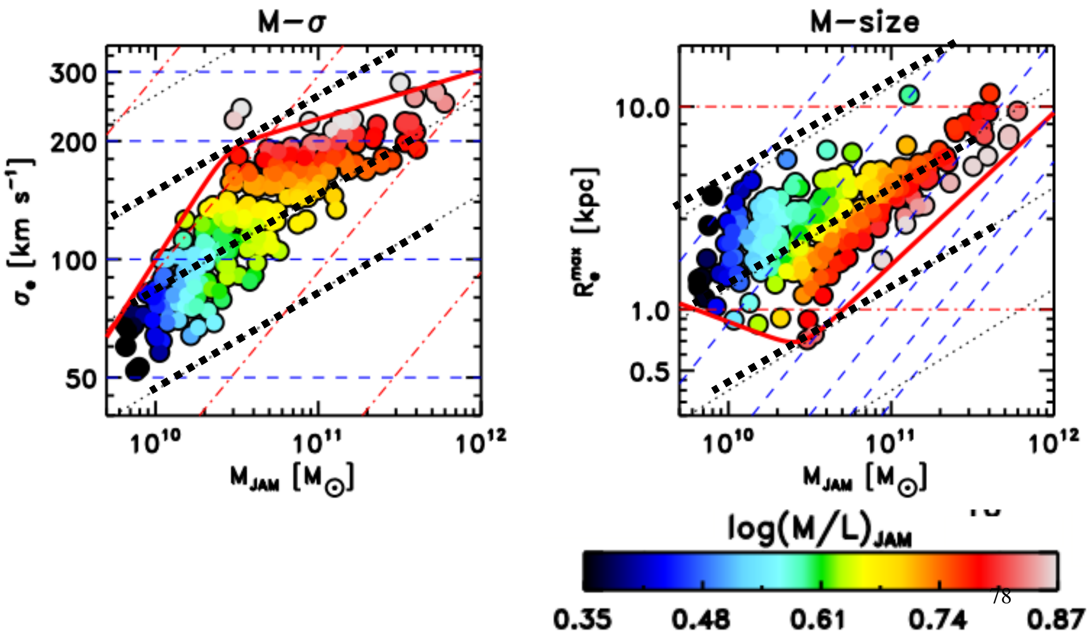


black points total mass, *open points stellar mass for two lensed galaxies*

Ferreras , Saha , and . Williams 2005

Detailed Analysis of Ellipticals

- More massive galaxies are larger and have high velocities and higher M/L- but not exactly as the virial theorm would predict (Black lines)



20 *M. Cappellari et al.*

Constraints on E Galaxy Growth
2 Processes??

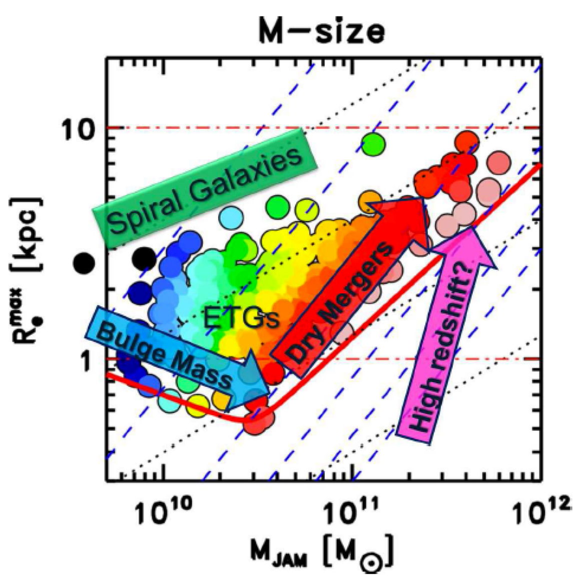


Figure 11. Evolution scenario for ETGs. The symbols are the same as in Fig. 1, while the large arrows indicate the proposed interpretation of the observed distribution as due to a combination of two processes (a) bulge or spheroid growth, which seems associated to the quenching of star formation, which moves galaxies to the right of towards the bottom, due to the increased concentration (decreasing R_e), and (b) dry merging, increasing R_e by moving galaxies along lines of roughly constant σ_e (or steeper), while leaving the population unchanged. A schematic illustration of these two processes is shown in Fig. 12.

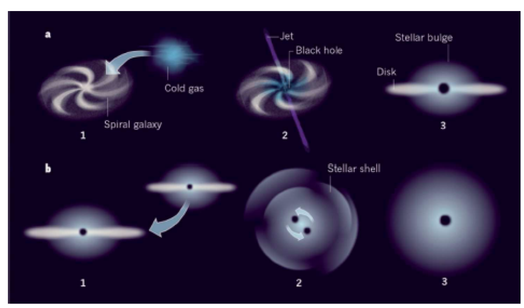


Figure 12. Schematic representation of the two main processes responsible for the formation of the observed distribution of galaxies on the VP. (a) bulge growth via cold accretion, secular evolution, or minor mergers, followed by quenching by AGN or other mechanisms, leaving the galaxy more massive, more compact, and consequently with a larger σ_e, and gas poor (blue arrow in Fig. 11); (b) major or minor dry mergers, increasing galaxy mass and sizes at nearly constant σ_e, or with a possible decrease, leaving the population mostly unchanged (red arrow in Fig. 11). (taken from Cappellari 2011b).

Bulge growth via slow accretion

Gas poor mergers

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 $M \sim kr\sigma^2/G$ 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.
- 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

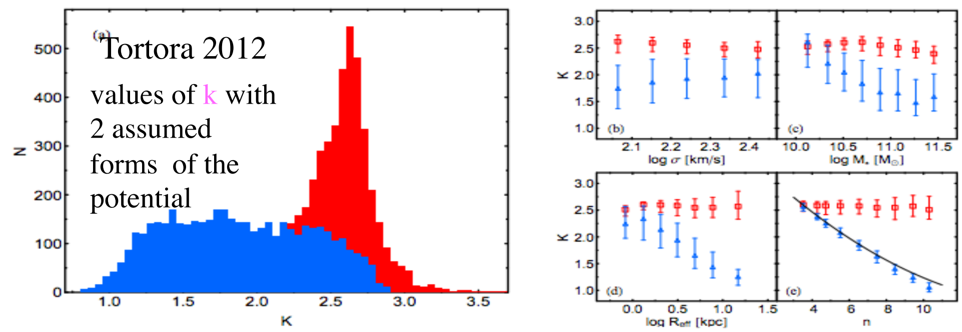


Figure 1. *Panel (a).* Distributions of K for SIS and const-M/L mass models (see Eq. (1)). *Panels (b-e).* Median value of K as a function of σ (b), M_* (c), $R_{\rm eff}$ (d), and n (e). Median values, with error bars showing 25–75 per cent scatter. Red and blue colours refer to SIS and const-M/L models, respectively. The black curve in panel (e) is taken from Bertin et al. (2002).

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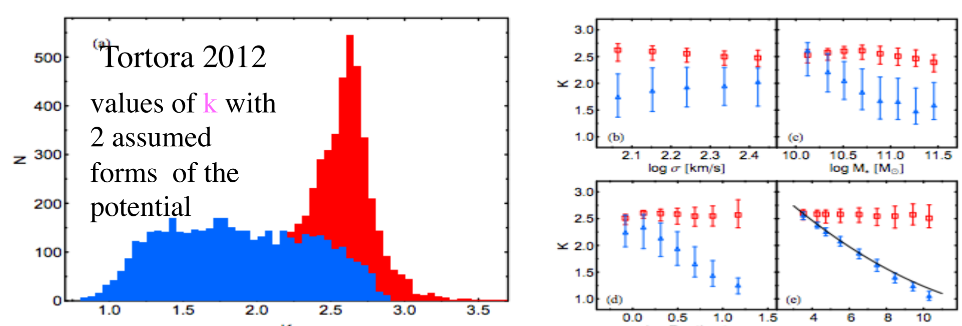

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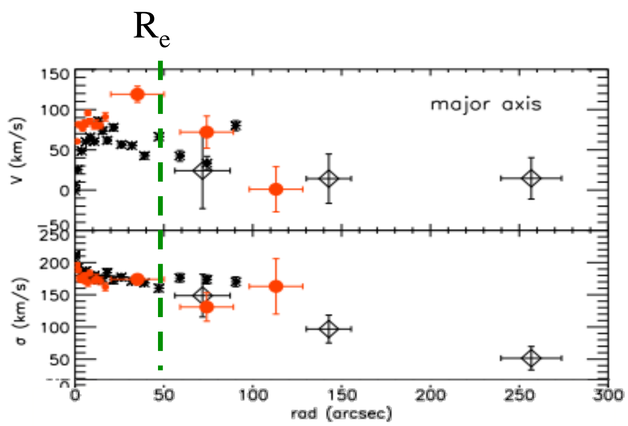
Detailed Fit for only a Few Objects at Large Radii

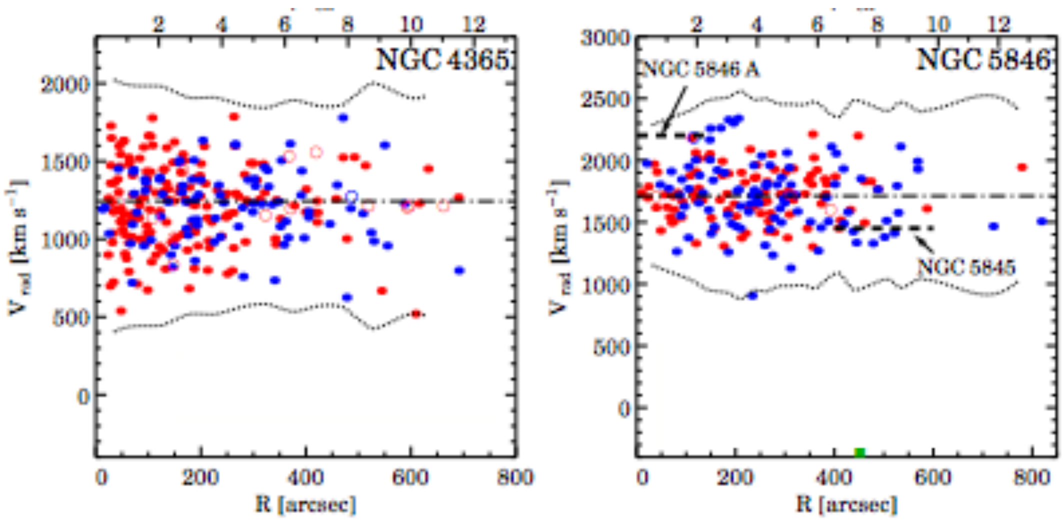
In order to fit the observed mildly declining or constant velocity dispersion profile without invoking dark matter at large radii, the orbits have to be tangentially anisotropic, while adding a dark halo results in more radially anisotropic orbits (!) - this is not seen requiring dark matter.

However the shape of the potential is not well determined

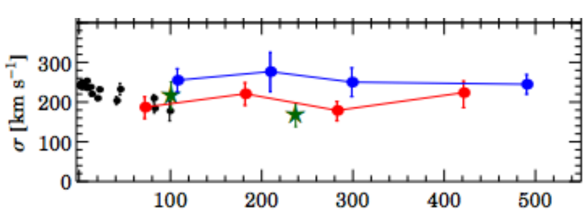


Weijmans et al 2010

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.

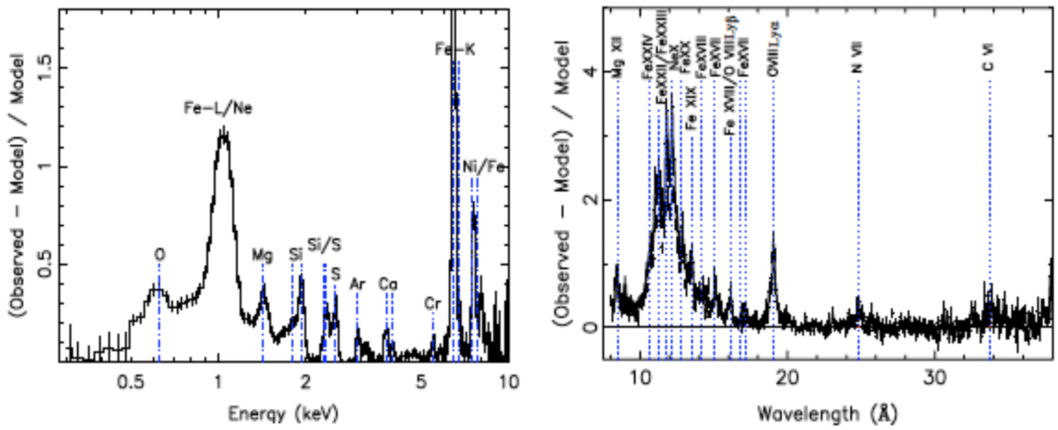
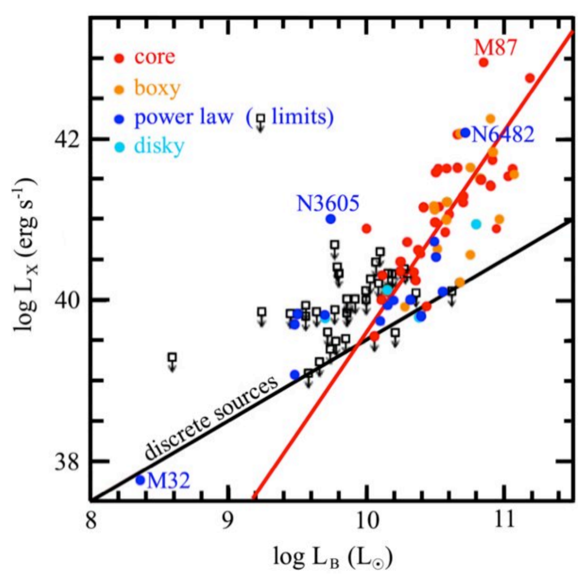


Fig. 31 *Left panel* The line spectrum of the cluster 2A 0335+096, as observed with *XMM-Newton* EPIC

X-ray Emission in Ellipticals

- 2 sources: x-ray binaries and hot gas. The ISM in most ellipticals is dominated by hot, kT~10^{6-7} K gas.
- The x-ray binary population is LMXBs (low mass x-ray binaries)
- Their x-ray spectra are very different.

- there is a relation between galaxy morphology and x-ray emission: *cored galaxies are x-ray hot gas luminous* - power-law galaxies do not contain significant X-ray-emitting gas.
- M_{gas}/M_*~0.01-0.001 100x less than in MW spirals - takes only10^8-10^{10} yrs to accumulate this gas from normal stellar mass loss - gas must be dynamic



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

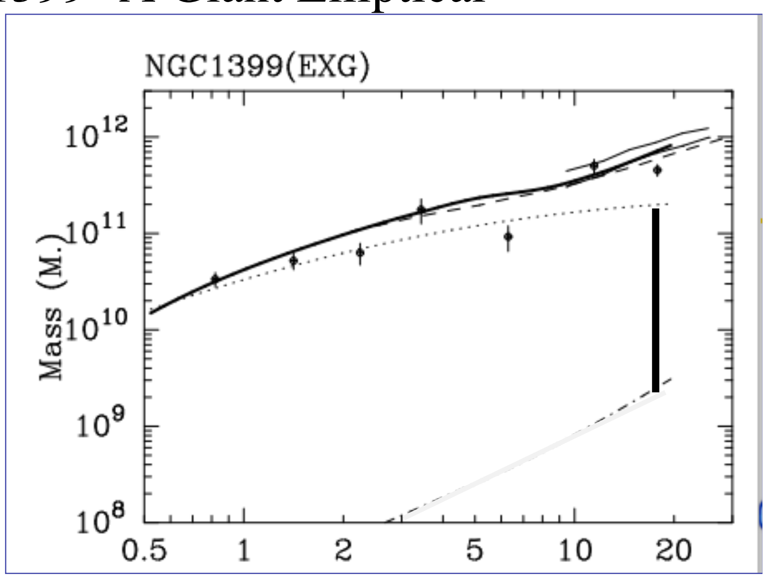
The temperature T_g from the spatially resolved spectrum

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

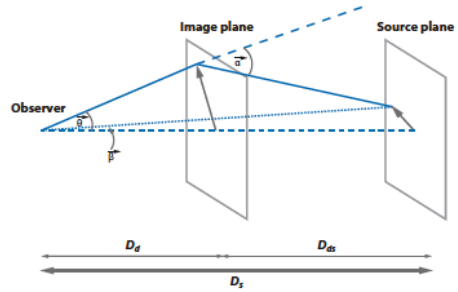
- Solid line is total mass
- dotted is stellar mass
- dash-gas mass is gas
- In central regions gas mass is ~1/500 of stellar mass but rises to 0.01 at larger radii
- Gas extends beyond stars (like HI in spirals)



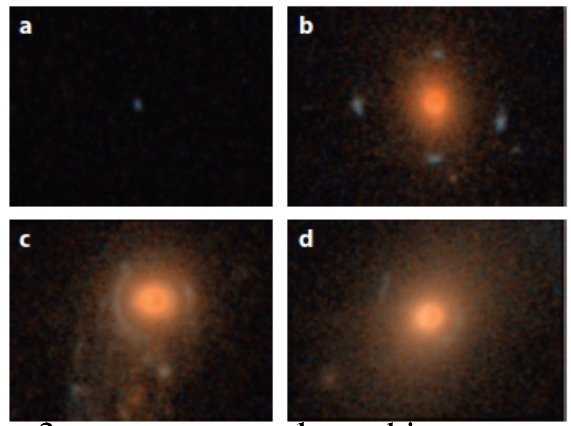
•Use hydrostatic equilibrium to determine mass $\nabla P = -\rho_g \nabla\phi(r)$ where $\phi(r)$ is the gravitational potential of the cluster (which is set by the distribution of matter) P is gas pressure and ρ_g is the gas density

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 88
quad, Einstein ring, a double

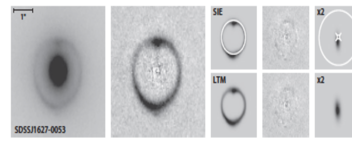
Lensing

- The earliest known mention of light being detected by massive objects is the first query in
- Newton's Opticks in 1704: 'Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action strongest at the least distance? (Treu and Ellis 2014 http://arxiv.org/pdf1412.6916v1.pdf

- 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
- **arXiv:1505.07450 Are the total mass density and the low-mass end slope of the IMF anti-correlated?**
- C. Spiniello, M. Barnabè, L.V.E. Koopmans, S.C. Trager

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-light 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

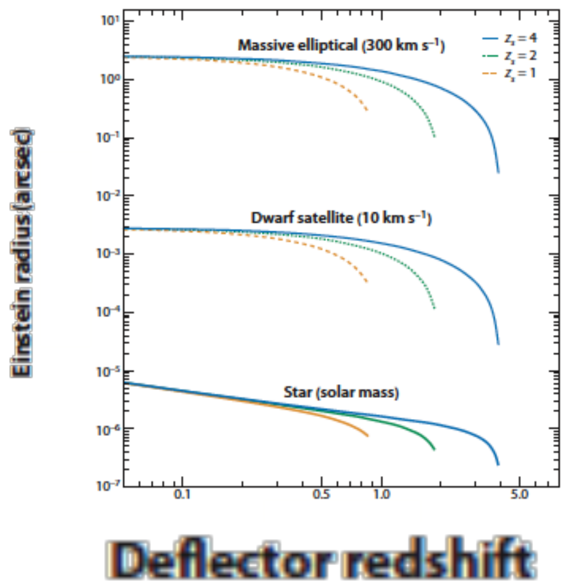
- It is rather difficult to determine whether dark matter is important in the central regions of ellipticals with just velocity and surface brightness data- lensing breaks the degeneracies

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 $\Sigma = c^2 D_s / (4\pi G D_d D_{ds})$

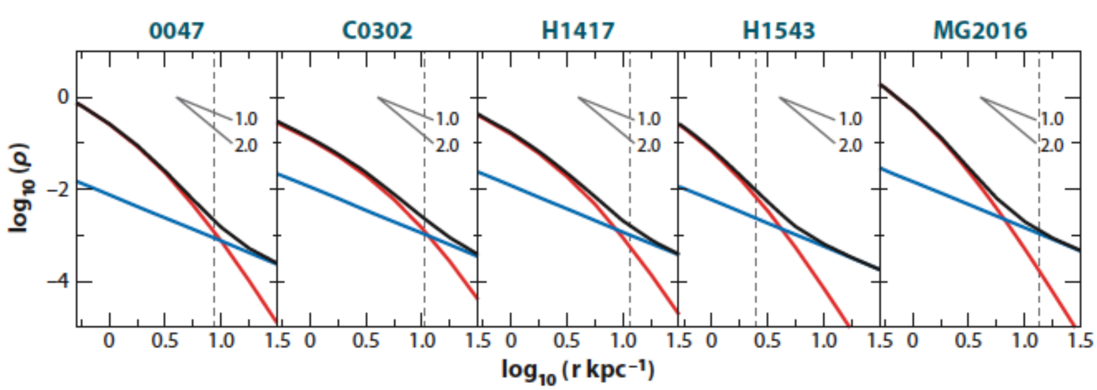
- Ellipticals Einstein radii are ~2" over a wide range of redshifts - but only 1/1000 galaxies are strong lenses
- cross section (Einstein radius^2) goes as σ^4. Ellipticals tend to have higher σ



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

Mass Profiles From Lensing + Photometry

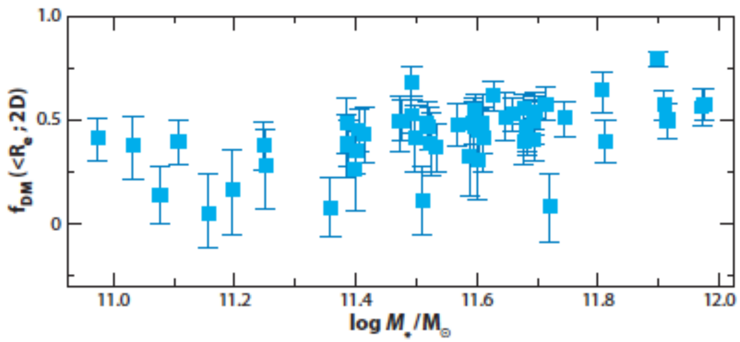
- Blue is mass density of dark matter, red that of stars for 4 galaxies (Treu 2010) as a function of radius (vertical line is Einstein radius)
- Dark dominates in all of these at large radii
- While neither stars nor DM have a power law distribution in density the sum does-similar to the disk-halo conspiracy 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 $r \sim R_e$ ~40% of the mass is dark, roughly independent of mass
- If we model the mass distribution as $d \log \rho_{tot} / d \log r = -\gamma$ we find that $\gamma \sim 2$ fits most objects ((Koopmans et al. 2009b).
- The small scatter around $\gamma = 2$ is remarkable considering that neither theDMhalo 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

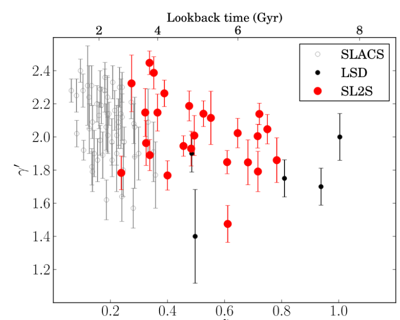
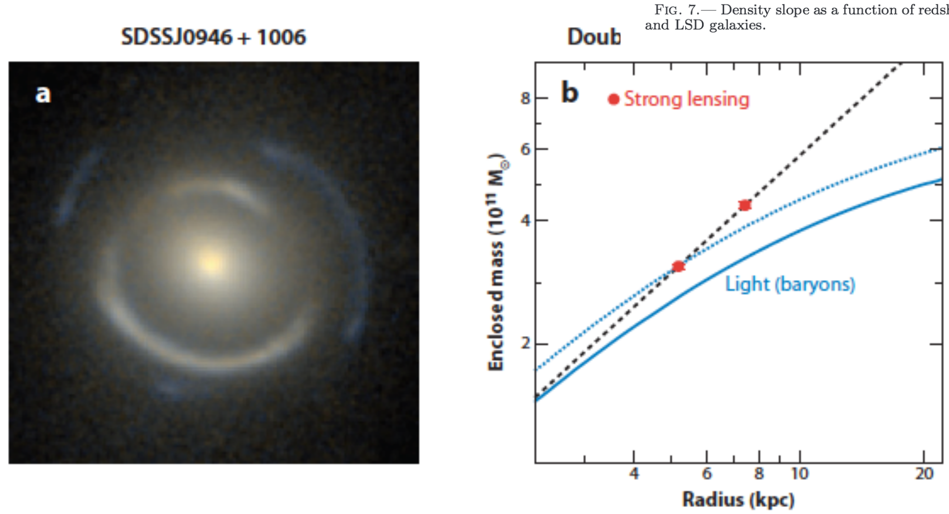


FIG. 7.— Density slope as a function of redshift for SL2S, SLACS and LSD galaxies.



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

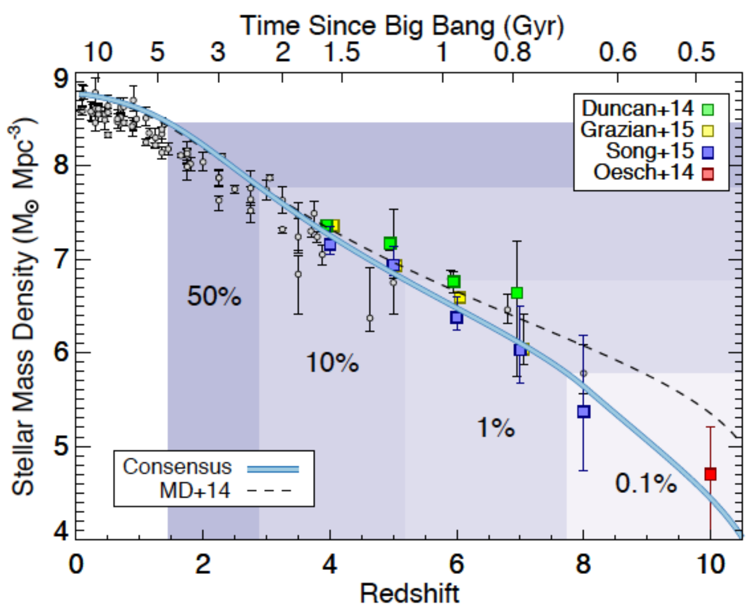
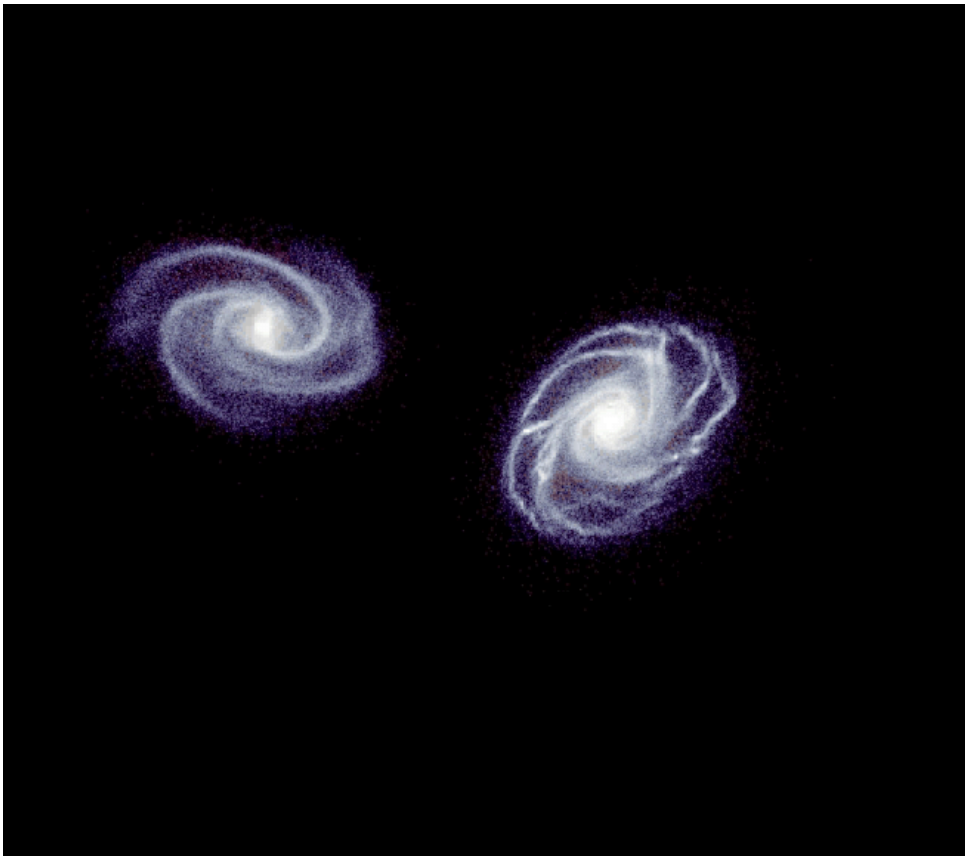
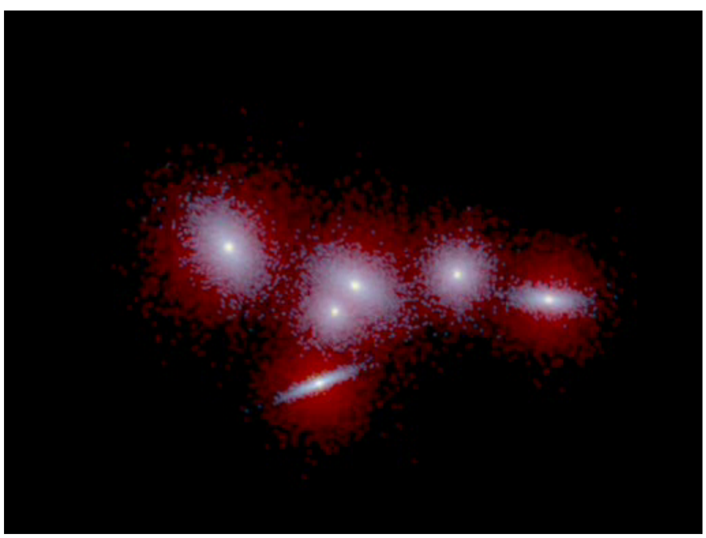


Figure 8. The evolution of the total stellar mass density in the universe, all derived assuming a Salpeter IMF. The low redshift



Computer simulation of galaxy collisions that make a big elliptical



J. Barnes, UH