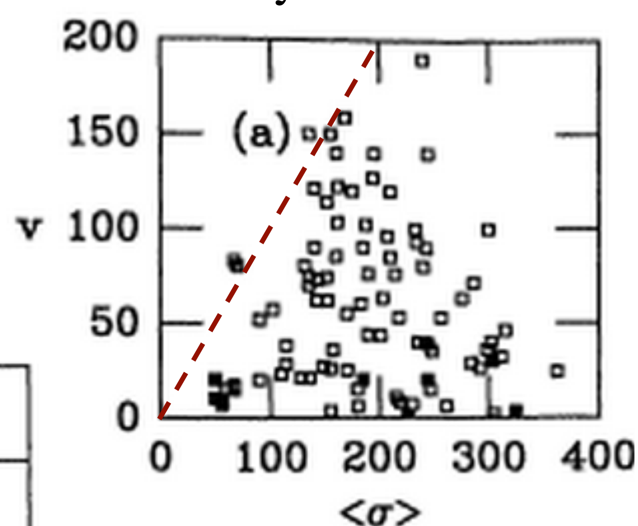
Summary So Far

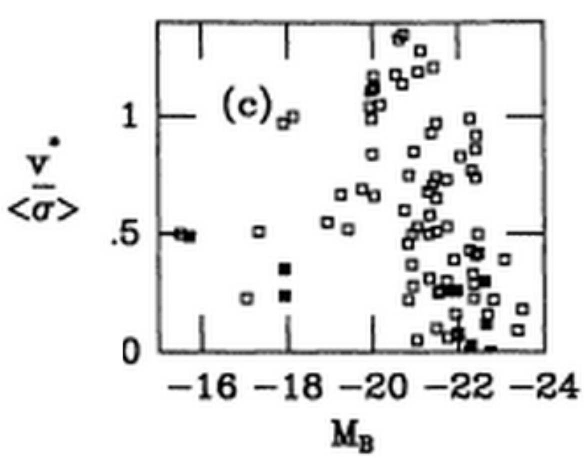
- Fundamental plane connects luminosity, scale length, surface brightness, stellar dynamics. age and chemical composition
  – - Faber Jackson relation L ~ σ^4
  – More luminous galaxies have deeper potentials
  follows from the Virial Theorem if
  M/L is constant

- Kinematics- massive ellipticals rotate very slowly, lower mass ones have higher ratio of rotation to velocity dispersion

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)



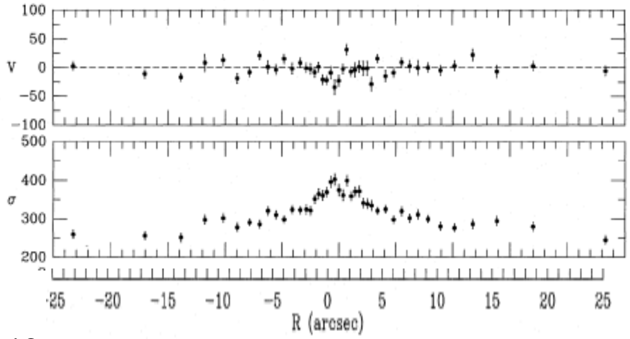


de Zeeuw and Franx 1991

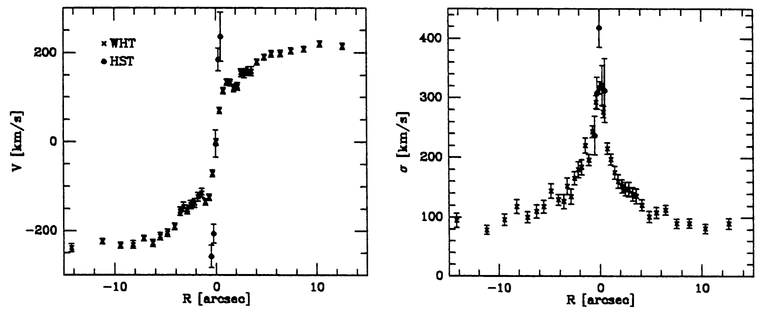
Kinematics

- 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

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

Observables:

- Spatial distribution and kinematics of "tracer population(s)",
  - stars in elliptical galaxies
  - globular clusters?
  - ionized gas (x-ray emission)
- 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.

…

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
  - a redshift/blue which is then converted to rotation
  - 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

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 stars

•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.

- $M(R)=(V^2r/G)+(r\sigma^2_r/G)[-d\ln\rho/d\ln r-d\ln\sigma^2_r/d\ln r-(1-\sigma^2_\theta/\sigma_r^2)-(1-\sigma^2_\phi/\sigma^2_r)]$
- 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

Orbits in Tri-axial Potential S&G 6.2.4

- Orbits in the x-y plane of a tri-axial potential
- $\phi(x,y)=1/2v_0^2\ln[R_e^2+x^2+(y^2/q^2)]$

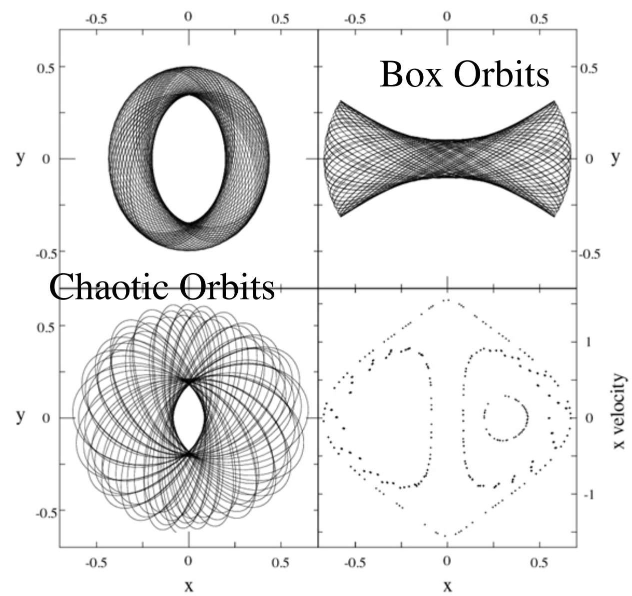
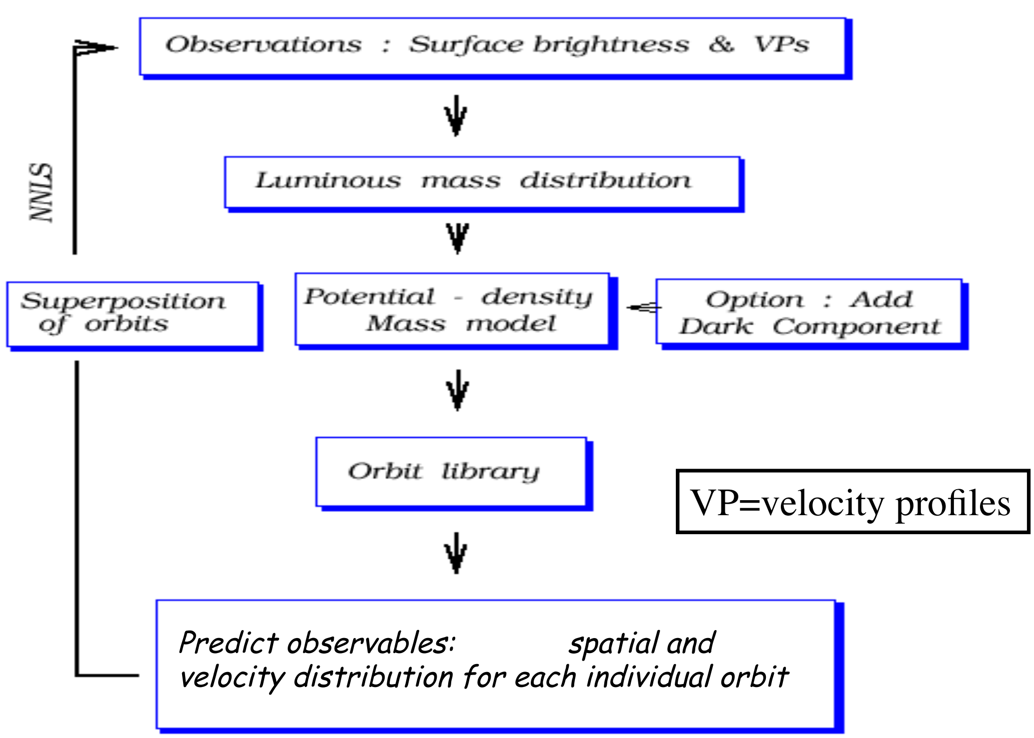


Fig 6.16 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



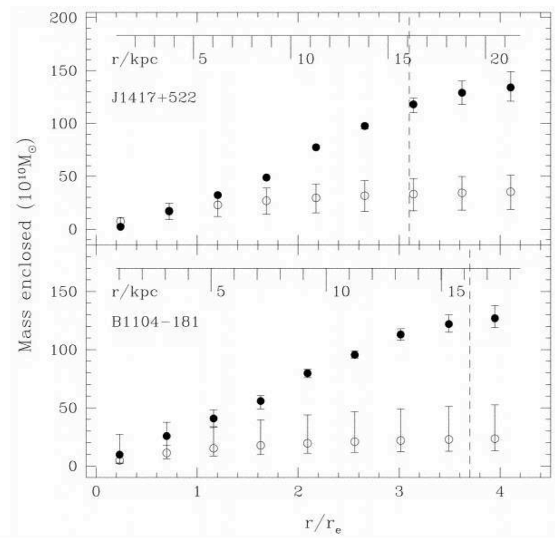
Degeneracies

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

Results

- The dark matter fraction increases as one goes to large scales and with total mass
- Density profile is almost isothermal

  dlog ρ_{tot}/dlog r ~r^{-2} which corresponds to a flat circular velocity profile

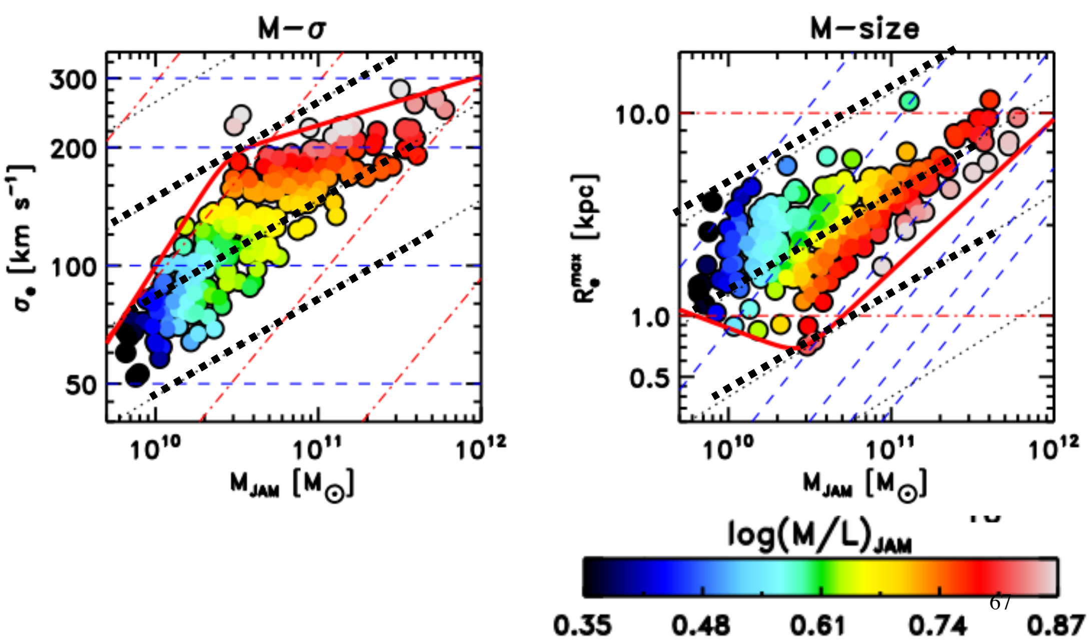


black points total mass, *open points stellar mass for two lensed galaxies*

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)



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.
- 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

X-ray Emission

- The temperature of the hot gas is set primarily by the depth of the potential well of the galaxy- it is ISOTROPIC
- 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.

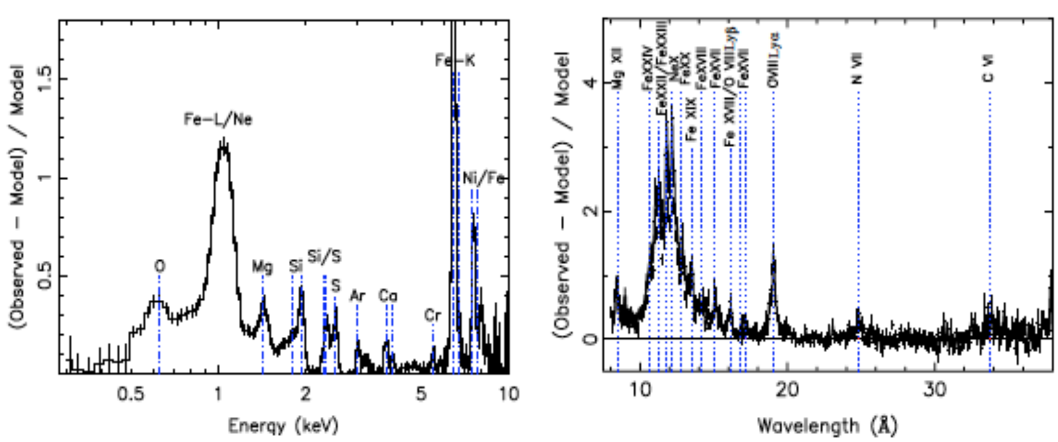


Fig. 31 *Left panel* The line spectrum of the cluster 2A 0335+096, as observed with *XMM-Newton* EPIC

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

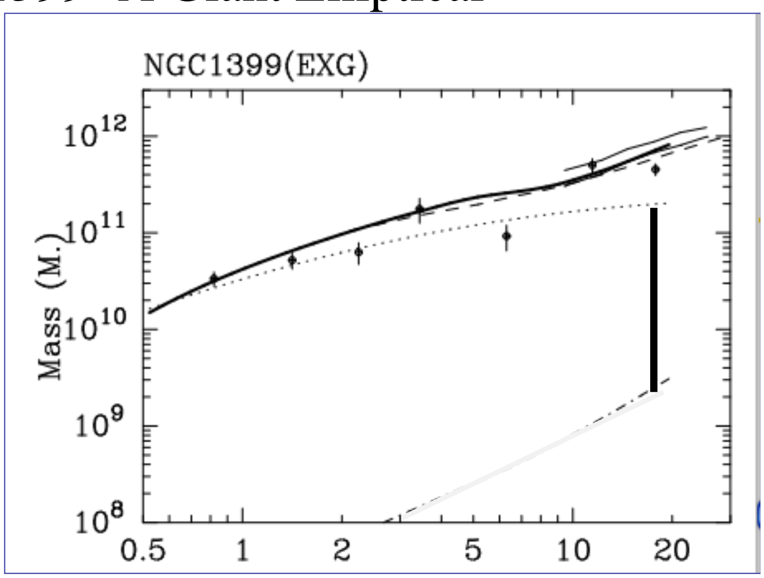
The temperature T_g from the spatially resolved spectrum

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

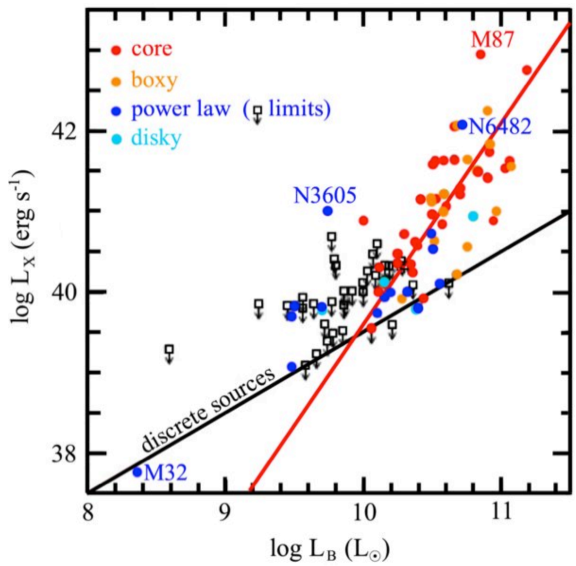
- Solid line is total mass
- dotted is stellar mass
- dash-gas mass is gas
- In central regions gas mass is ~1/500 of stellar mass but rises to 0.01 at larger radii
- Gas extends beyond stars (like HI in spirals)



•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

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

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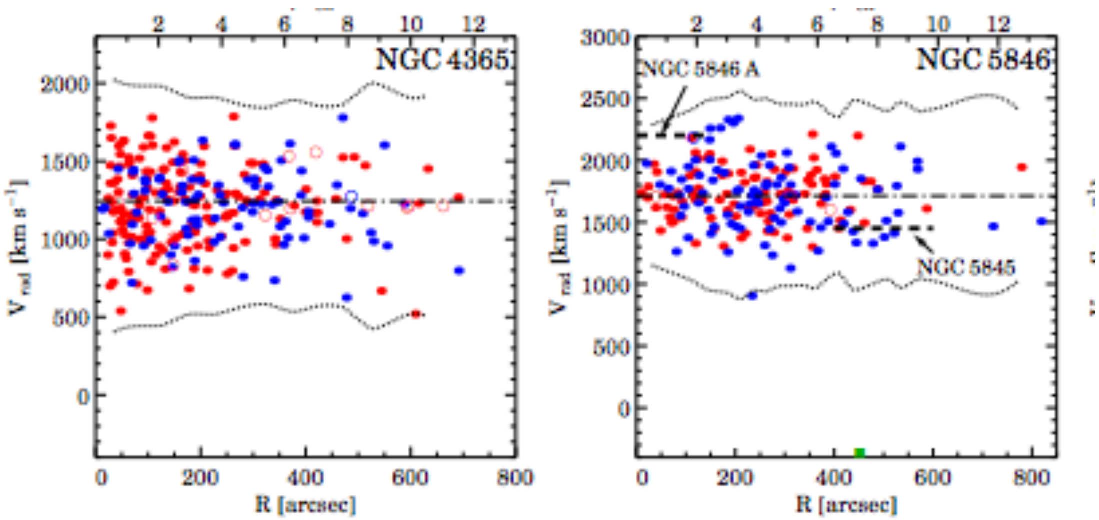
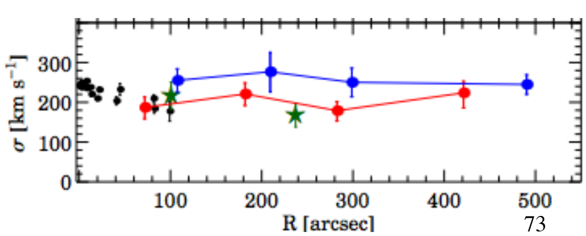
Velocity field of globular clusters- use like stars in MW



- 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



Gravitational lensing…Sec 7.4 of S&G

- In some cases, can also measure galaxy mass using gravitational lensing.
- Get good agreement with dynamical measurements

Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Lensing

- Angle of change

$\alpha \sim 4GM/bc^2 = 2R_s/b$

- where R_s is the Schwarzschild radius and b is the impact parameter
- Background images are distorted and amplified.
- Einstein radius θ_E

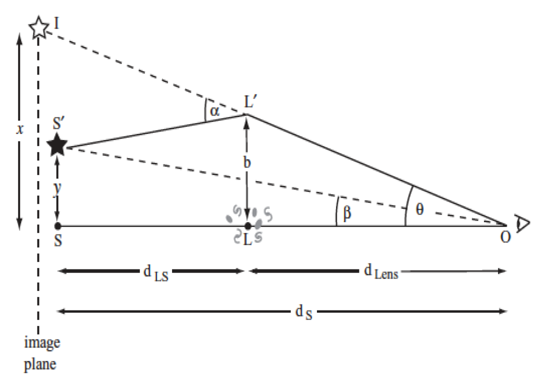
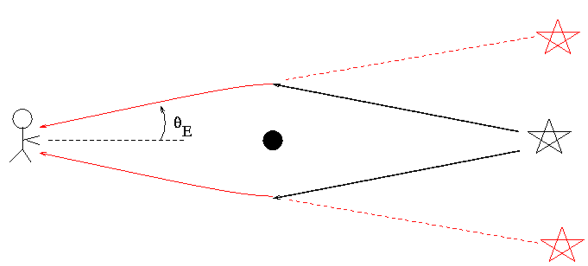
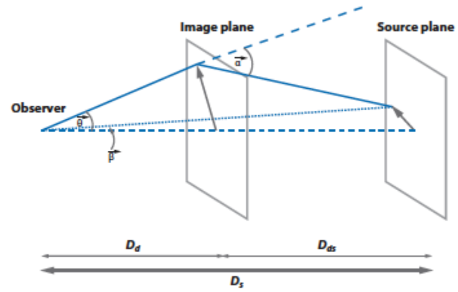


Fig. 7.14. The gravity of the mass $\mathcal{M}$ at L bends light from a distant source at S′ toward the observer at O; the source appears instead at position I.

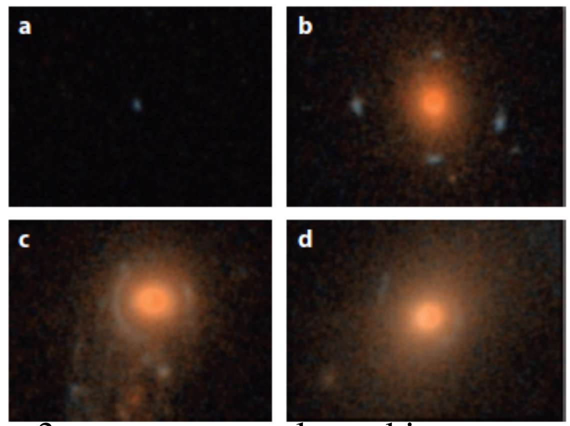


Lensing- S&G 7.4.1,7.4.2

- 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



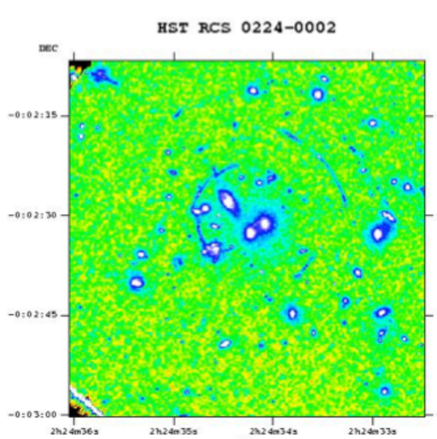
- dynamical models provide masses enclosed within a *spherical* radius, while strong lensing measures the mass inside a *cylinder* with axis parallel to the line-of-sight
- Einstein radius $\theta_e = 4\pi(\sigma_{sis}/c)^2 D_{ls}/D_s$ $= (\sigma_{sis}/186 \text{ km s})^2 D_{ls}/D_s$ arcsec
- where, 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

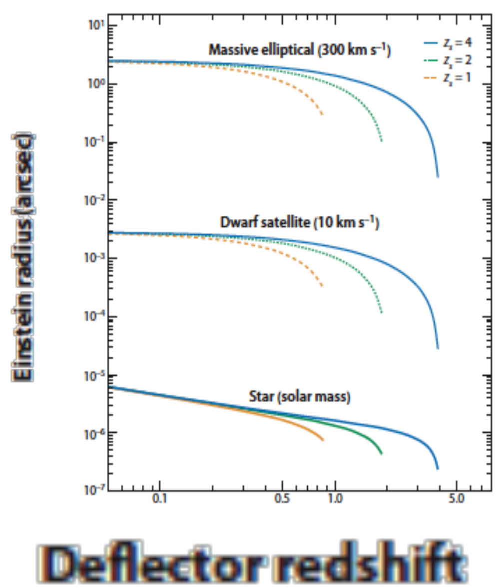


3 most common lensed images quad, Einstein ring, a double

Why Giant Ellipticals as Lenses

- To 1st order strong lensing is only sensitive to the mass enclosed by the *Einstein radius*
- 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

Gravitational Lensing Elliptical Galaxies- see Strong Lensing by Galaxies ARAA 2010 T. Treu and sec 6.6 in MBW

- Gravitational lensing, by itself and in combination with other probes, can be used to great effect to measure the mass profiles of early-type galaxies, both in the nearby universe and at cosmological distances (Treu & Koopmans 2002a,b)
- Model the total (dark matter + stars) mass profile as a spherical power law $\rho(r) \sim r^{-\gamma}$ in the kinematic analysis.
- The free parameters of the model are the slope γ, and the mass normalization.
- The data required for this inference are the Einstein radius of the lens, the redshift of both the deflector galaxy and the lensed source, and the velocity dispersion of the lens.

For a point mass the Einstein radius is

$\theta_E=[(4GM/c^2)\ D_{LS}/D_L D_S]^{1/2}$

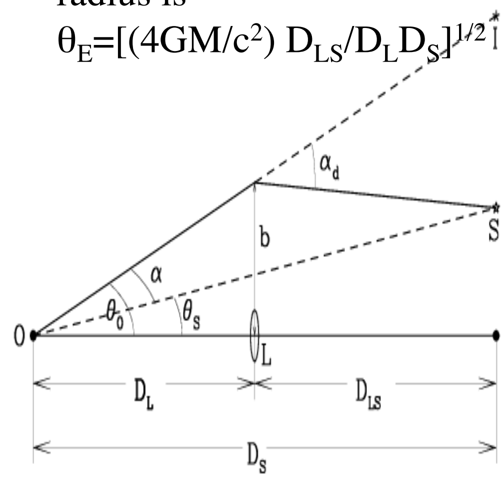
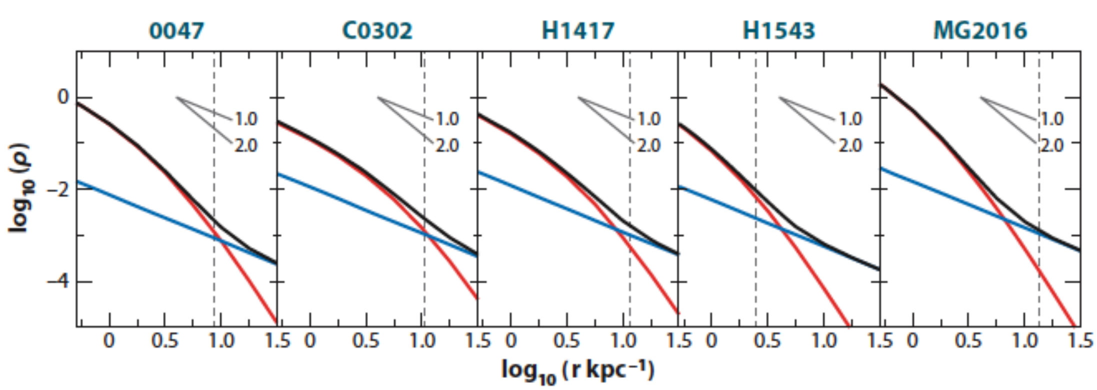


FIG 6.6 IN MBW

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

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 are made in mergers, but disks are not.