Summary So Far

- Fundamental plane connects luminosity, scale length, surface brightness, stellar dynamics. age and chemical composition
  - Elliptical galaxies are not randomly distributed within the 3D space (R_e, σ, I_e), but lie in a plane
  - Faber Jackson relation L ~ σ^4-follows from the Virial Theorem if M/L is constant
- All massive early-type galaxies have an age–luminosity relation
  - less massive galaxies have younger stellar populations, in an SSP sense.
  - This is called cosmic downsizing; the *least massive galaxies* continue to form stars until present, while the *most massive galaxies* stopped forming stars at an early epoch

Narrow range of colors and mass vs indicates ages , metallicity and shape of the potential fall in a narrow pattern

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

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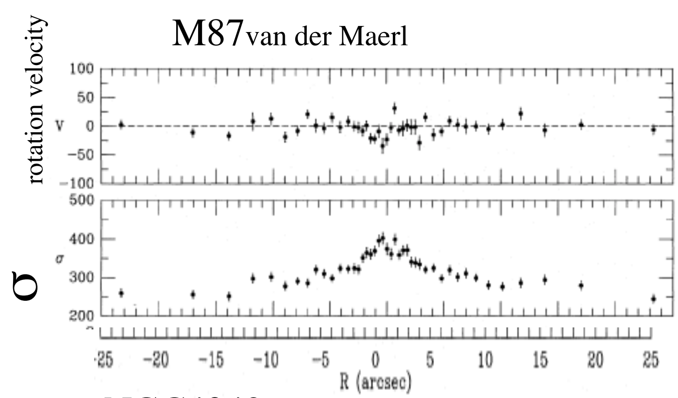
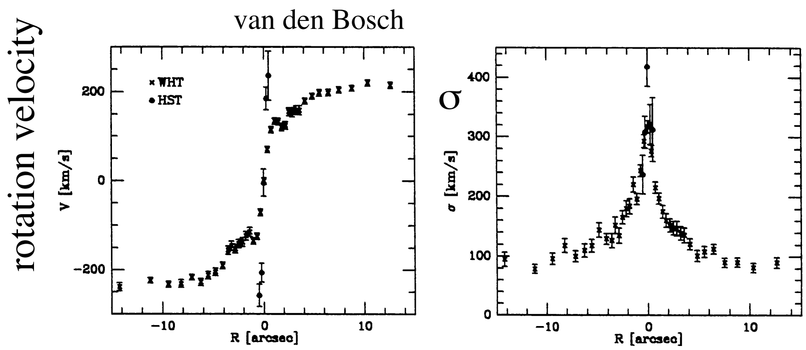
Kinematics

- Kinematics- the features used to measure the velocity field are due to stellar absorption lines: which are 'blurred' by projection and the high velocity dispersion (σ) of the galaxies.
- 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

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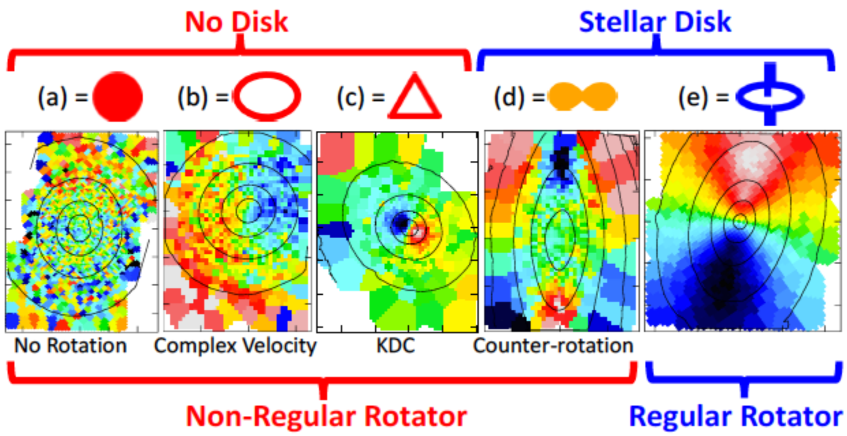
New 2-D Data

- Now have much more information... very complex will not cover in class (Cappellari 2014)



color corresponds to velocity in line of sight, red is red shifted wrt to systemic, blue is blue shifted

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

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)
  - "cool" gas (small fraction of objects)
- In external galaxies only 3 of the 6 phase-space dimensions, are observable $\Sigma\ (x_{proj}),\Sigma(y_{proj}),v_{LOS}$!- remember the Jeans eq (Σ surface brightness of the star light);v_{LOS} contains some information about the 3-D velocity field

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

Said Another Way

Assuming steady state a galaxies dynamics is fully specified by
(i) the six-dimensional stellar distribution
function (DF), the distribution of the positions and velocities of stars in the galaxy,
(ii) by the gravitational potential, or equivalently the total mass distribution, including stars and dark matter
However with only 2-D data this is an intrinsically degenerate and non-unique problem.
This is because the DF is a function of the three isolating integrals of motion (Jeans 1915) and one cannot uniquely constrain both the 3-dim DF and the 3-dim mass distribution using only a 3-dim observable, since the the deprojection of the stellar surface brightness into an intrinsic stellar luminosity density is mathematically non unique,

Dynamics of Ellipticals

- More complex than spirals- 3D system (1 velocity distribution 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
- $(1/\rho)d(\rho\langle v_r\rangle^2)/dr+2\beta/r\langle v_r\rangle^2=-d\phi/dr$
- where ϕ is the potential and β is the anisotropy factor $\beta=1-\langle v_\theta\rangle^2/\langle v_r\rangle^2$
- Since $d\phi/dr=GM_{tot}(r)/r^2$ one can write the mass as

- **$M_{tot}(r)=r/G\langle v_r\rangle^2\ [d\ln\rho/d\ln r+d\ln/\langle v_r\rangle^2/d\ln r+2\beta]$**
- expressed in another way

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

- **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 !
- Rotation and random motions (σ-dispersion) are both important.

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
- $(1/\rho)d(\rho\langle v_r^2\rangle)/dr)+2\beta(r)v^2/r=-d\phi/dr$

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

$$\beta(r) = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2} = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$$

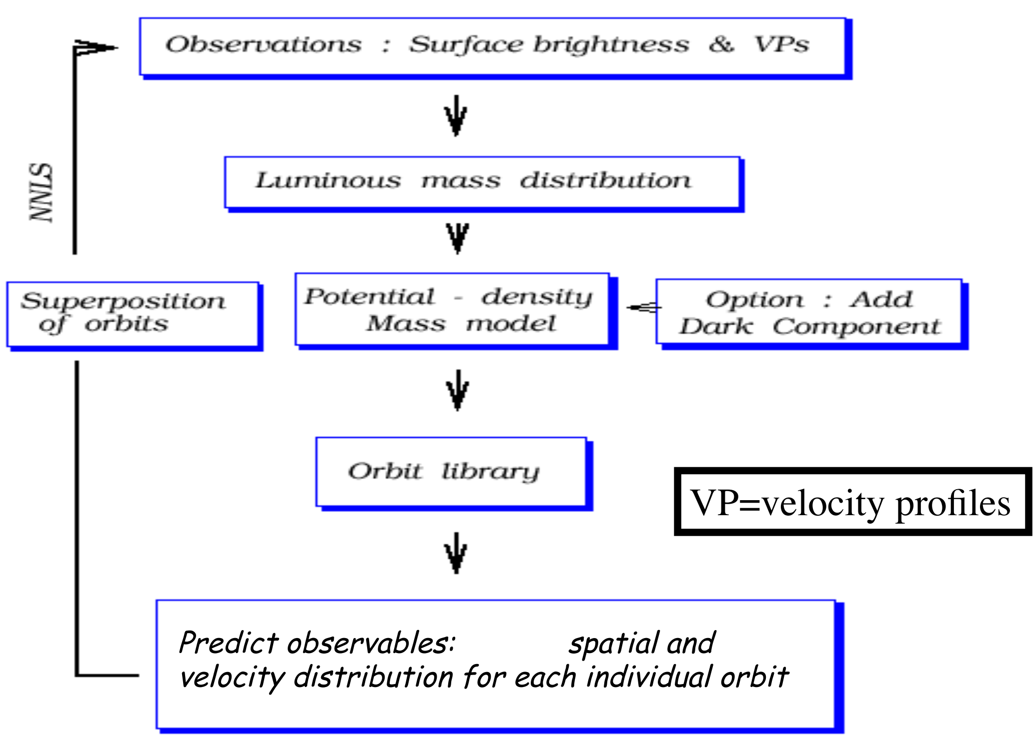
- $\beta = 1, 0, -\infty$ radial, isotropic, and circular orbits, respectively

re-write this as $M(R)=-(\langle v_r^2\rangle r/G)[d\ln n/d\ln r+d\ln v_r^2/d\ln r+2\beta]$

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

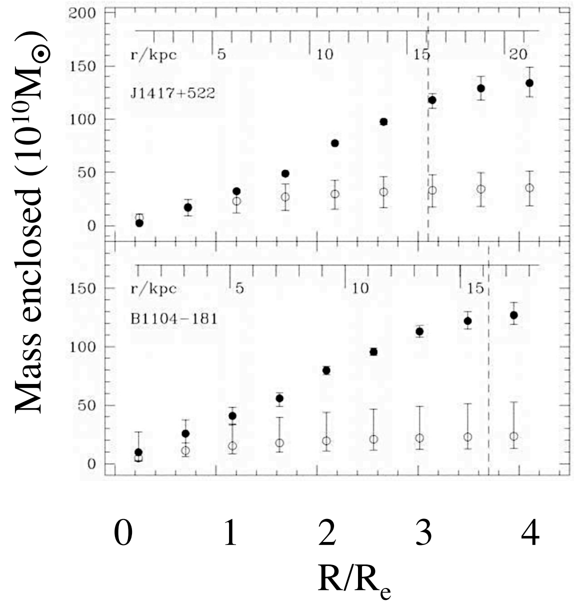
$\sigma^2_p(R)=2/I(R)\int(1-\beta R^2/r^2)\rho v^2\,[r\,dr/\mathrm{sqrt}(r^2-R^2)]$

no unique solution since the observable $\sigma^2_p(R)$ depends on both v_r^2 and β



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



black points total mass, *open points stellar mass for two lensed galaxies* (difference is Dark matter)

Ferreras , Saha and Williams 2005

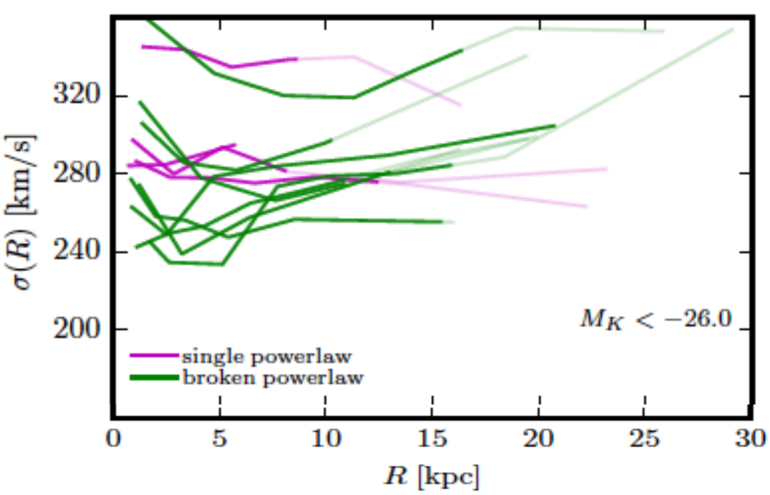
General Results

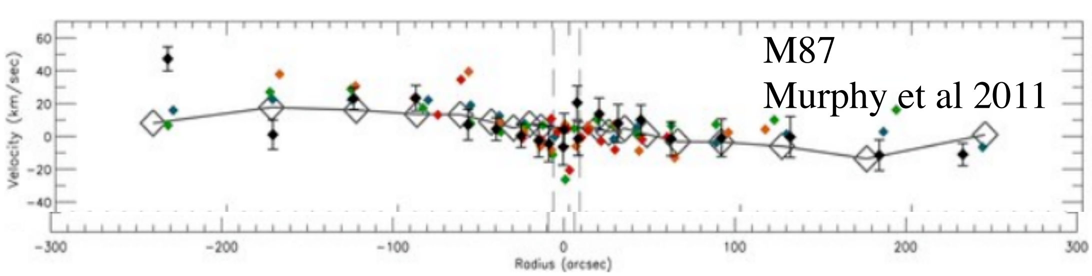
- The dark matter fraction increases
  - as one goes to large scales
  - and with total mass
- Density profile is almost isothermal

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

New Data

- Spatially 2D resolved kinematics out to large radii are now possible. (Veal et al 2016

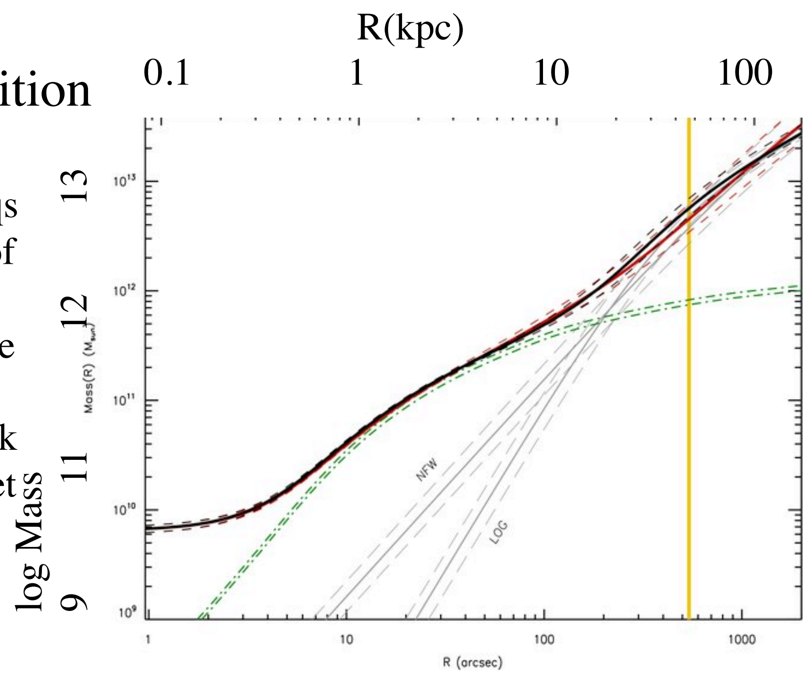




100"=7.8kpc

Mass Decomposition

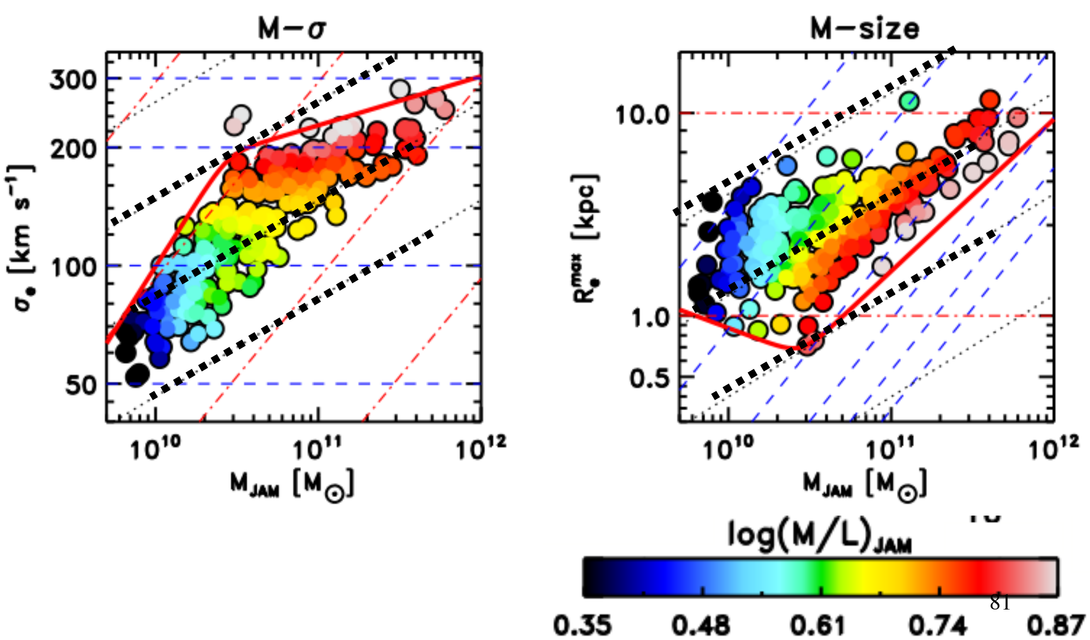
- Using dynamical data, the Jeans eqs and an estimate of M/L for the stars one can derive the decomposition into stars and dark matter (Murphy et al 2011)



Black= total mass
Green= stellar mass

Detailed Analysis of Ellipticals

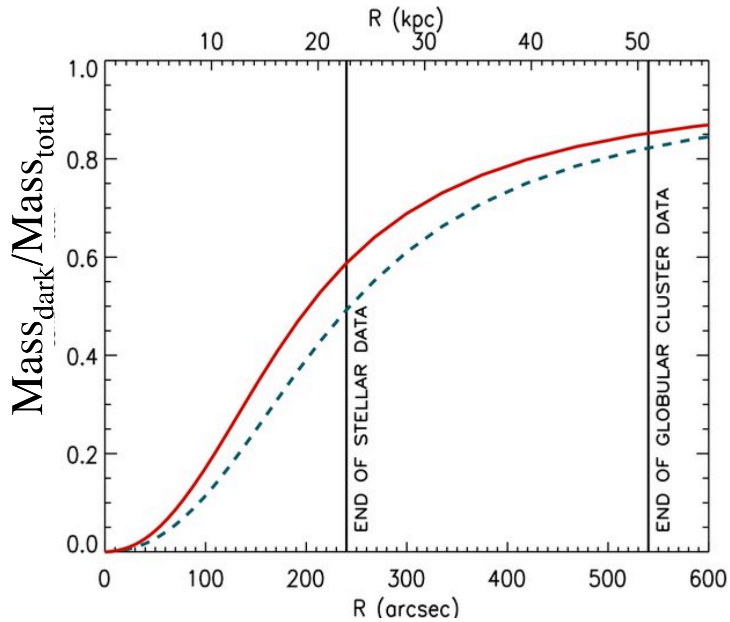
- More massive galaxies are larger and have high velocities and higher M/L- but not exactly as the virial theorm would predict (Black lines)



Dark Matter Dominates at Large Radii

- Murphy et al 2011 M87 data
- for more material see **Structure and Kinematics of Early-Type Galaxies from Integral-Field Spectroscopy**

Michele Cappellari
arXiv:1602.04267



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- evidence for a dark matter halo**
- 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.

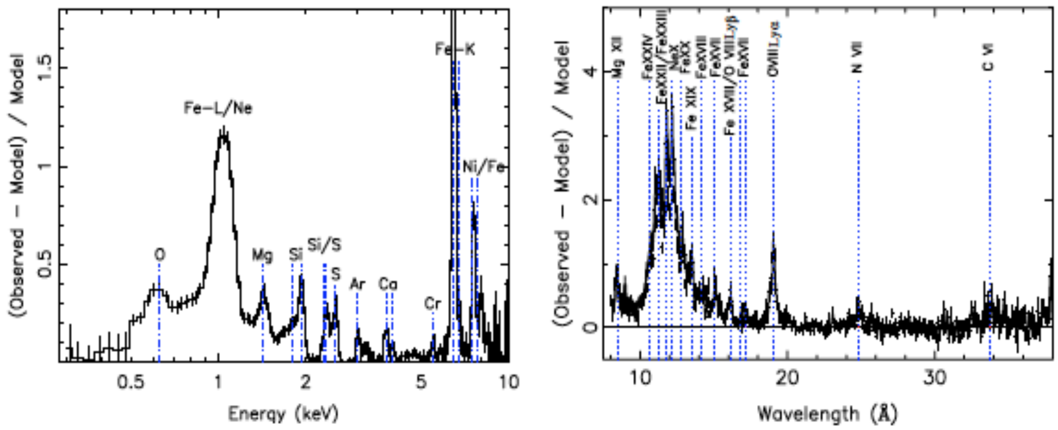


Fig. 31 *Left panel* The line spectrum of the cluster 2A 0335+096, as observed with *XMM-Newton* EPIC

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

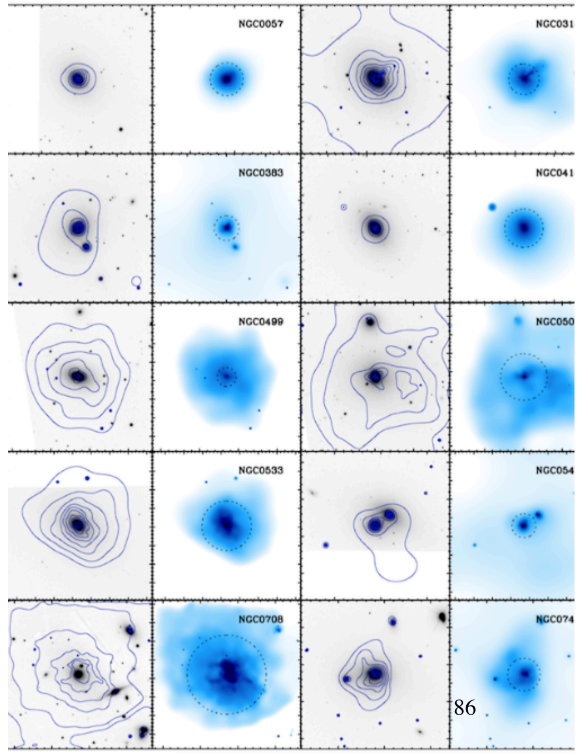
The temperature T_g from the spatially resolved spectrum

The density ρ_g from the knowledge that the emission is due to bremmstrahlung

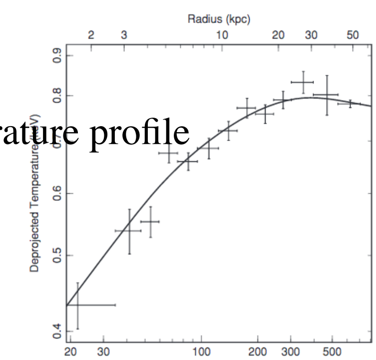
And the scale size, **r**, from the conversion of angles to distance

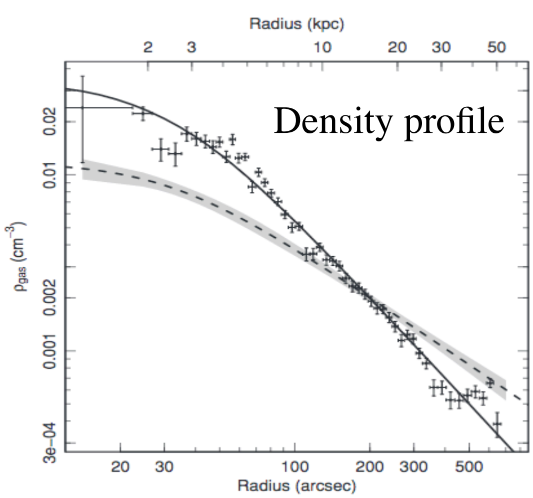
X-rays Extend to Large Radii

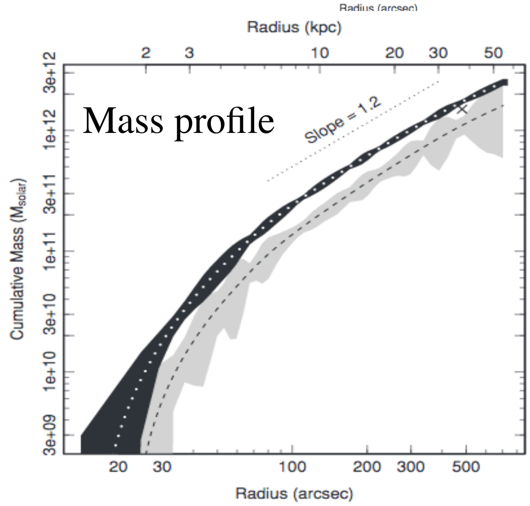
- X-ray and optical images of elliptical galaxies (Goudling et al 2016)
  - (dotted circle is R_e)



Use of the Data





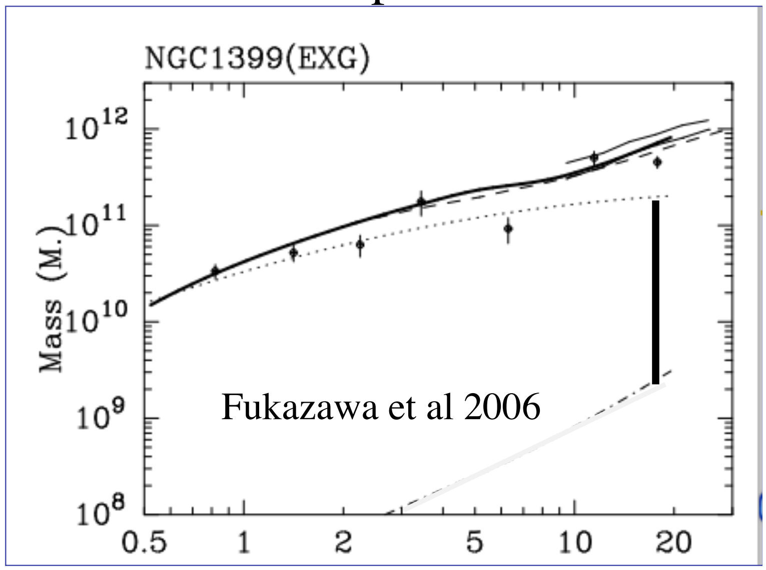


NGC1399- A Giant Elliptical

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)

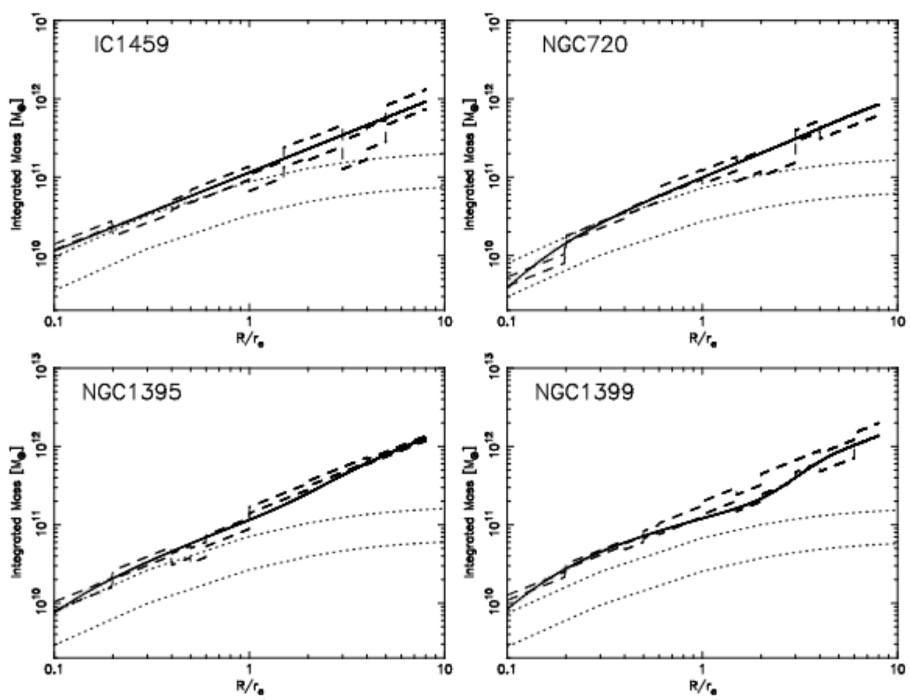


•Use hydrostatic equilibrium to determine mass

$$\nabla P=-\rho_g \nabla \phi(r)$$

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 Masses
- Frequentl can determine mass at r>>R_e
- Dark matter dominate: at r>>R_e



nagino and Matsushita 2009

Problems with X-rays

- Have to assume hydrostatic equilibrium- not clear how accurate this is.
- Only ~12 bright sources which are not in groups of galaxies
- Surface brightness is dropping rapidly, hard to go to large radii without very deep exposures.
- Typical scatter between 'x-ray' and 'optical' masses 30% but no systematic differences

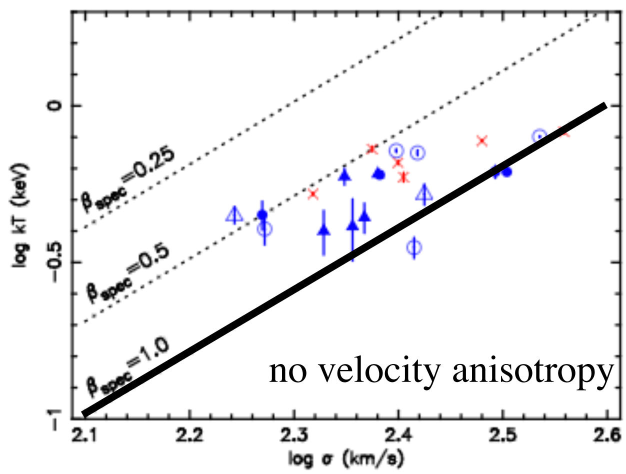
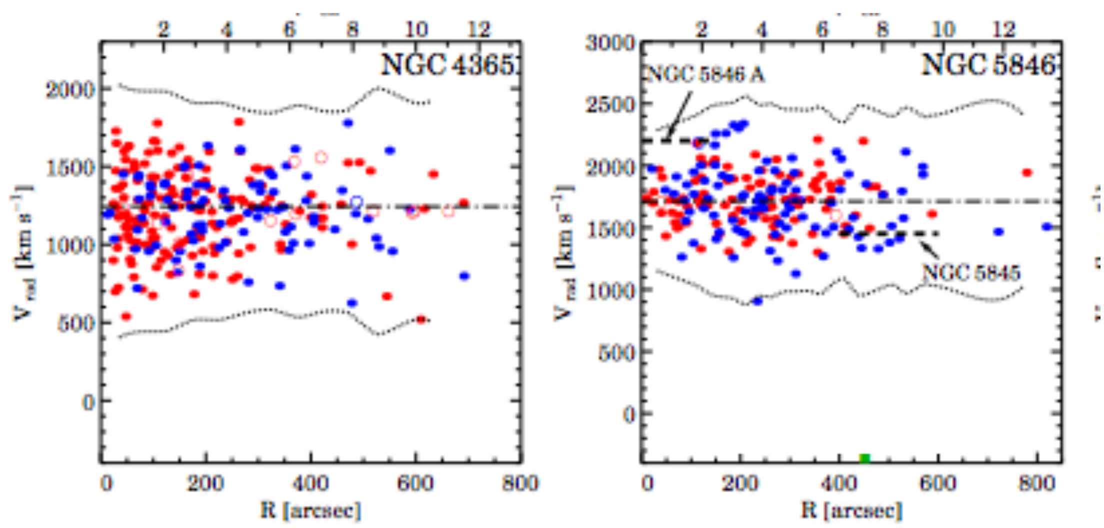
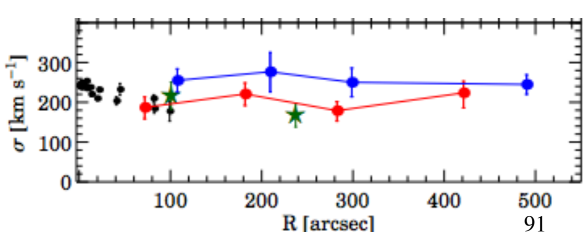


Fig. 9. Central ISM temperatures plotted against central st

Velocity field of globular clusters- use like stars in MW

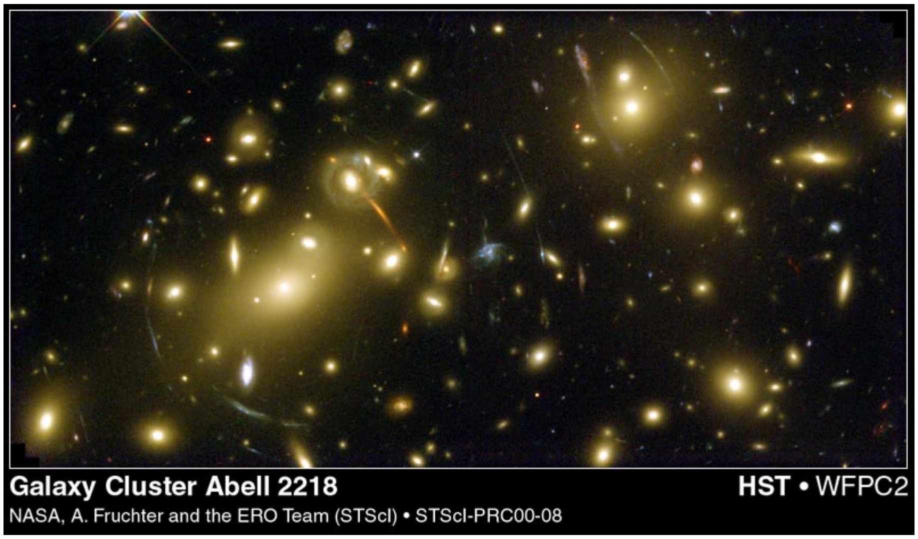


- Some of the galaxies show a very flat velocity dispersion profile for the globulars out to large radii- evidence for dark matter or fine tuned anisotropy profiles



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



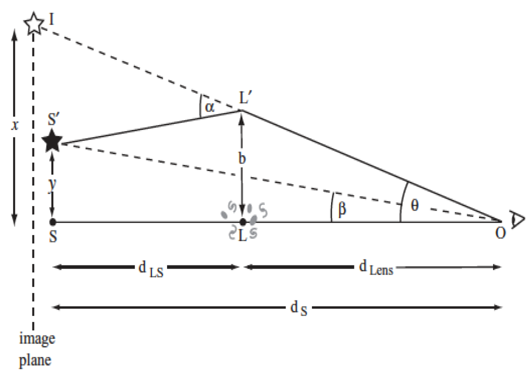
Lensing

- Angle of change

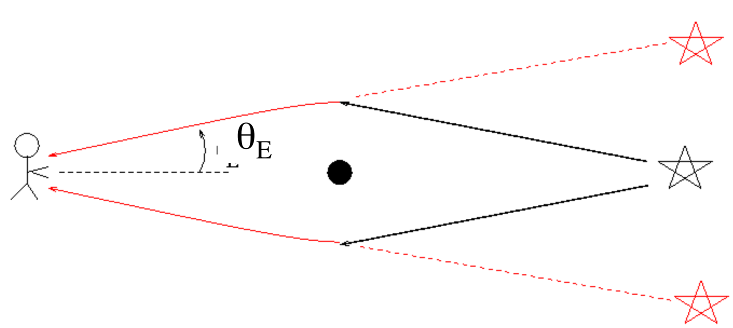
$\alpha \sim 4GM/bc^2 = 2R_s/b$

- where R_s is the Schwarschild radius and b is the impact parameter
- Background images are distorted and amplified.
- Einstein radius for an isothermal sphere is

$\theta_E = \theta_e = 4\pi(\sigma_{sis}/c)^2 D_{ls}/D_s \sim (D_{ls}/D_s)(\sigma^2/186\text{km/sec})''$

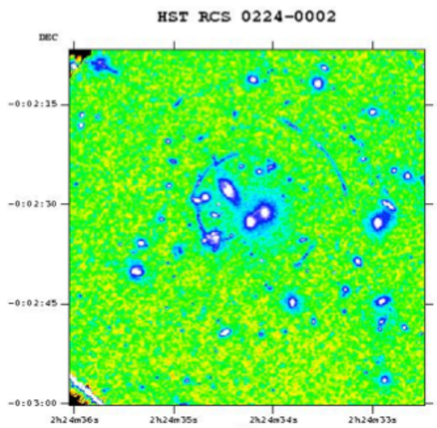


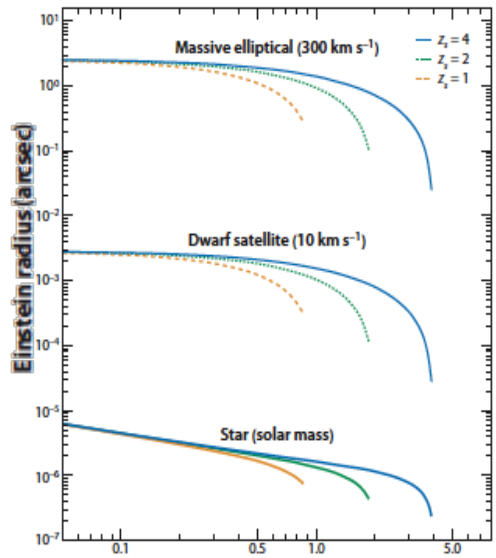
θ_E
Fig. 7.14. The gravity of the mass $\mathcal{M}$ at L bends light from a distant source at S′ toward the observer at O; the source appears instead at position I.



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



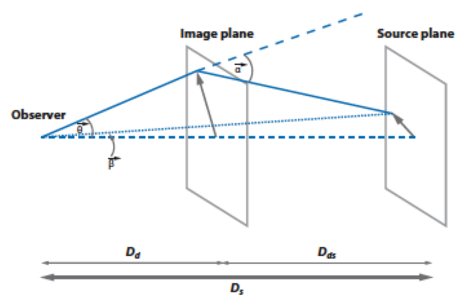


Deflector redshift

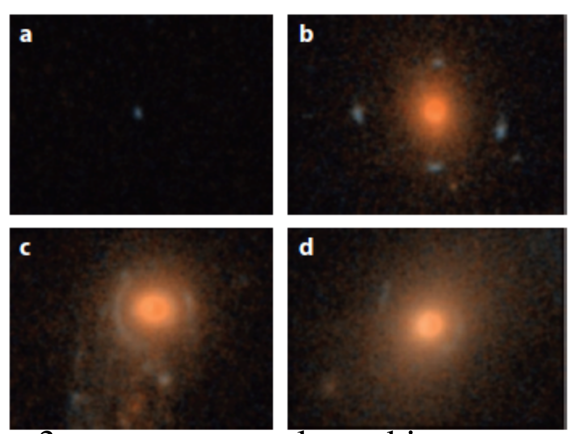
Treu 2010

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

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

- Gravitational lensing, can 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 $\rho(r) \sim \rho(0)\, r^{-\gamma}$
- Need:
  – 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
$\theta_E=[(4GM/c^2)\, D_{LS}/D_L D_S]^{1/2}$

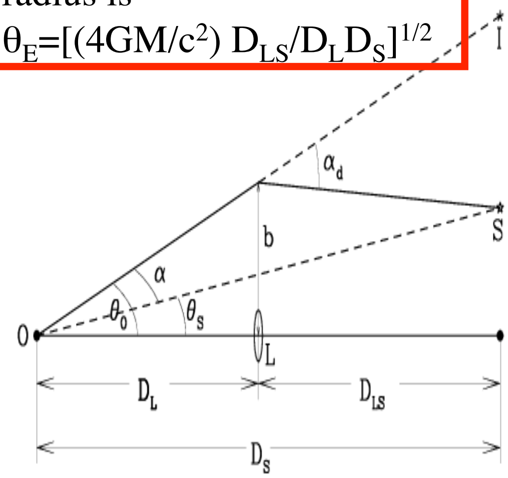
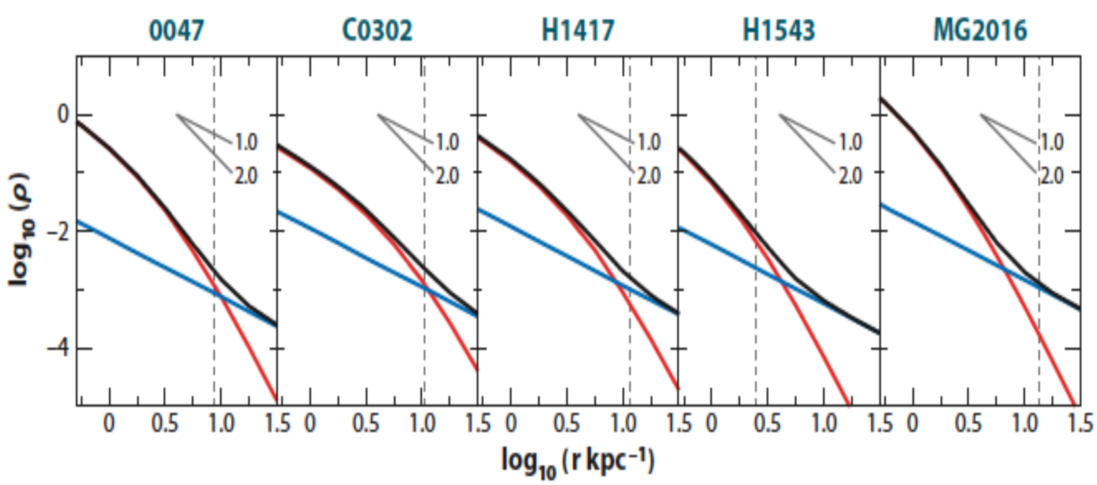


FIG 6.6 IN MBW

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**
- Notice that *inner regions are dominated by stellar mass*



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

Shells

- The incidence of mergers inferred from shells- they come from the merger of a small with a big galaxy

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Why Interesting

- The surface brightness profiles are a hint to the formation process
- hierarchical clustering implies that different galaxies are the products of different merger histories in which different progenitor morphologies and encounter geometries produced a variety of results.
- It is remarkable that the remnants of such varied mergers shows so much regularity (Kormendy 2009)

There are several simple types of mergers

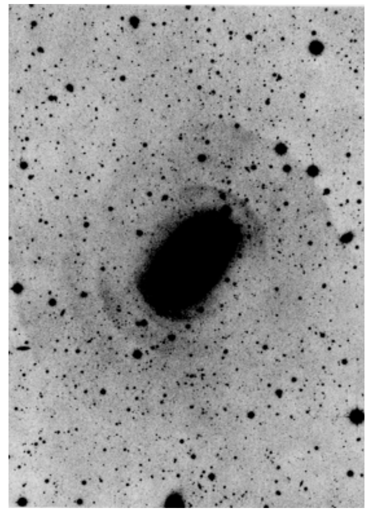
- wet (lots of cold gas)- e.g. spiral x spiral
- dry (little cold gas)- elliptical x elliptical
- wide range of mass (dwarf into normal)

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

.

Deviations from Sersic

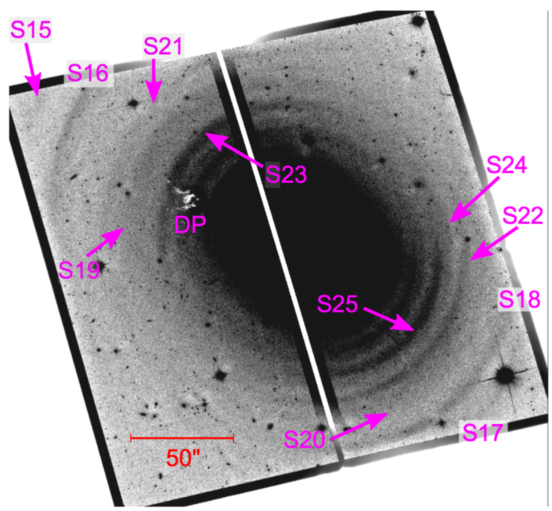
- ~10-20% of ellipticals show 'ripples'- indicative of a merger (MBW ***13.3.5 Merging Signatures)***



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

Shell Formation

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



NGC3923 Bilek et al 2015

The 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

- This helps to explain why supermassive BHs correlate with bulges but not disks
- bulges and ellipticals are made in mergers, but disks are not.
- Disks are formed via smooth accretion of diffuse gas, which largely conserves its angular momentum,
- spheroids are formed via gas-poor mergers that efficiently transfer angular momentum
- But correctly reproducing the structural scaling relations and their evolution for both disks and spheroids, as well as the correct overall evolution of the number densities of these two populations, remains an open challenge.

What are the Differences

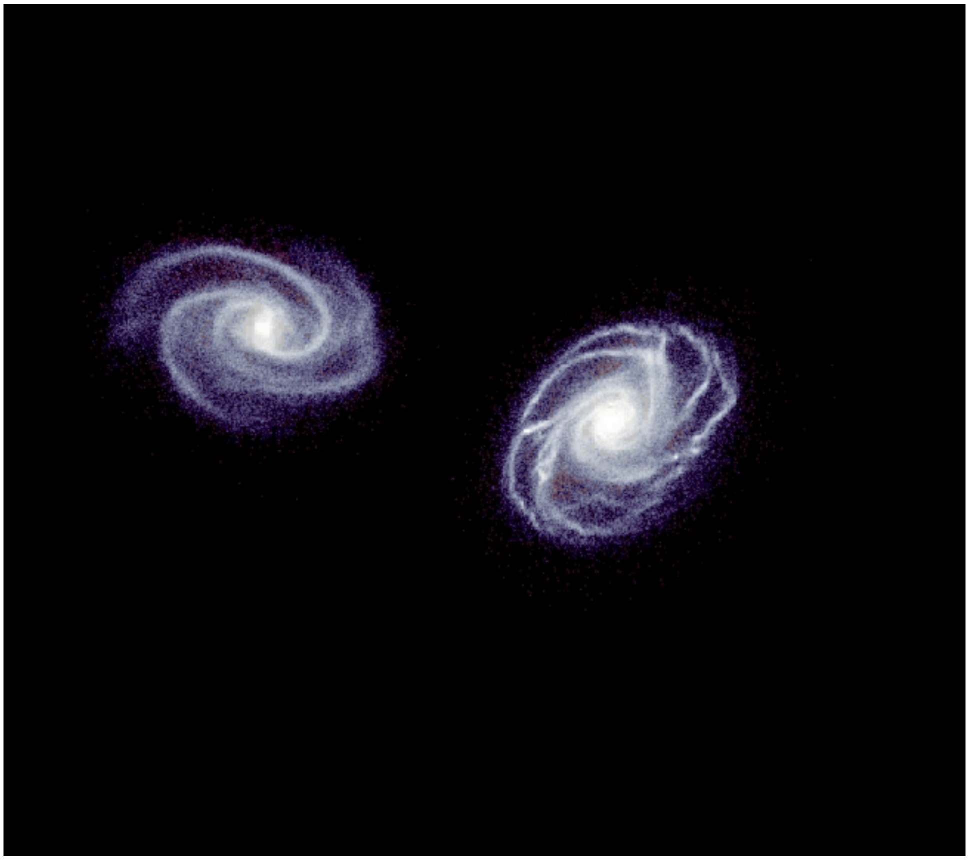
i) Monolithic Dissipative Collapse

- Early massive gas cloud undergoes dissipative collapse
  - Huge starburst during collapse
    - Very luminous high redshift objects detected with high SFR.
  - Clumpiness during collapse
      - violent relaxation

(ii) Hierarchical Mergers

  - Early universe much denser: e.g. $z \sim 2$ density ~ 27 times higher than today.
  - Mergers/interactions probably common.
  - Sequence of galactic mergers, starting with pre-galactic substructures
  - Galaxies continue to grow during $z \sim 1$-2
    - old ellipticals at $z \sim 1$ already exist
  - Galaxies fall into clusters and merging ceases (encounter velocities too high)

- Both process seem to be necessary varying from object to object over cosmic time



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End of Ellipticals