Summary of Abundance Data

- All early-type galaxies obey a metallicity–luminosity relation
  - less massive galaxies are less metal rich
  - outer regions have lower abundances but similar abundance ratios
  - weak age gradients
- All massive early-type galaxies have an age–luminosity relation
  - less massive galaxies have younger stellar populations, in an SSP sense.
  - This is called cosmic downsizing; many of the *least massive galaxies* continue to form stars until present, while the *most massive galaxies* stopped forming stars at an early epoch

Final Exam and Project

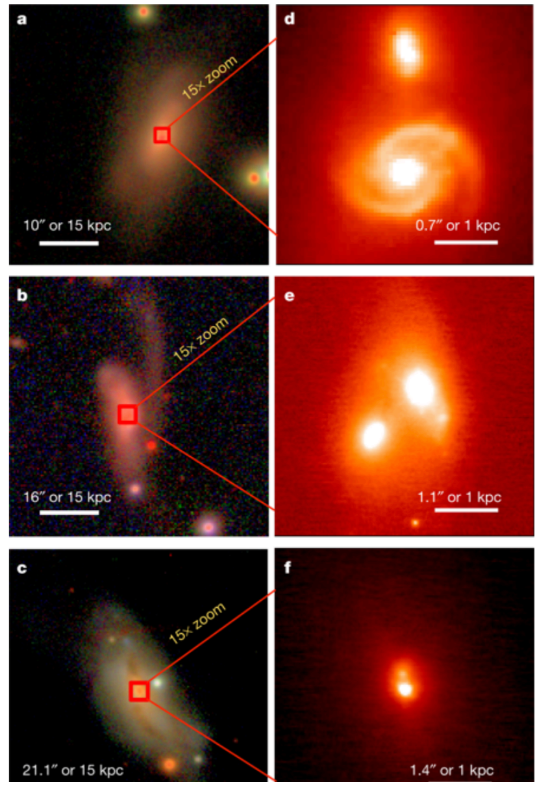
Final

Monday Dec 17 1:30 pm - 3:30 pm this room

deadline for project Dec 4

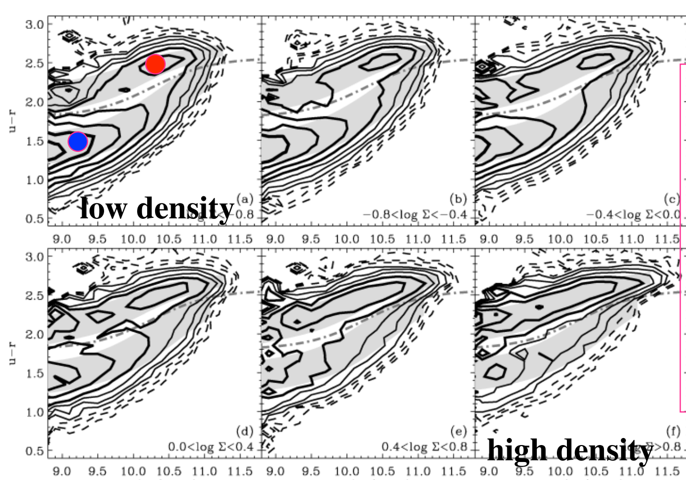
- **A population of luminous accreting black holes with hidden mergers**
- Michael J. Koss, Laura Blecha, Phillip Bernhard, Chao-Ling Hung, Jessica R. Lu, Benny Trakthenbrot, Ezequiel Treister, Anna Weigel, Lia F. Sartori, Richard Mushotzky, Kevin Schawinski, Claudio Ricci, Sylvain Veilleux & David B. Sanders

Fig. 1: Example images of final-stage mergers.



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

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

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

  - BUT if ellipticals are primarily formed by mergers, made in regions where mergers are more frequent, but galaxies are not moving too fast (otherwise not merge)

Faber-Jackson S&G 6.2.2

- Roughly, L ~ σ^4
- – More luminous galaxies have deeper potentials
- follows from the Virial Theorem (see derivation of Tully- Fisher, but now use σ instead of $v_{circular}$)
- Dimensional analysis $\sigma^2 \propto GM/R$ and thus $R \propto \sigma^2 I^{-1} (M/L)^{-1}$
- compared to actual fit of $R_e \propto \sigma^{1.4} I^{0.9-}$ these are consistent if $(M/L) \propto M^{0.2}$
- More detailed analysis shows that the the intrinsic scatter and tilt of this relation is driven by stellar population variations, including the stellar initial mass function

$$\frac{L_V}{2 \times 10^{10} L_\odot} \approx \left(\frac{\sigma}{200\,\mathrm{km\,s^{-1}}}\right)^4.$$

Fundamental plane

6 observables are all correlated via **the fundamental plane**
Luminosity, Effective radius, 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 with Mass

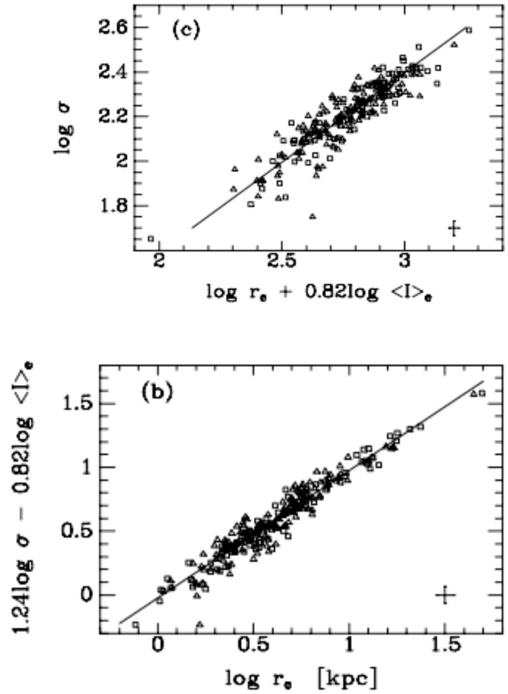
Fundamental Plane-relates structural/dynamical of Ellipticals to their stellar content.

Three key observables of elliptical galaxies, effective radius R_e, 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.



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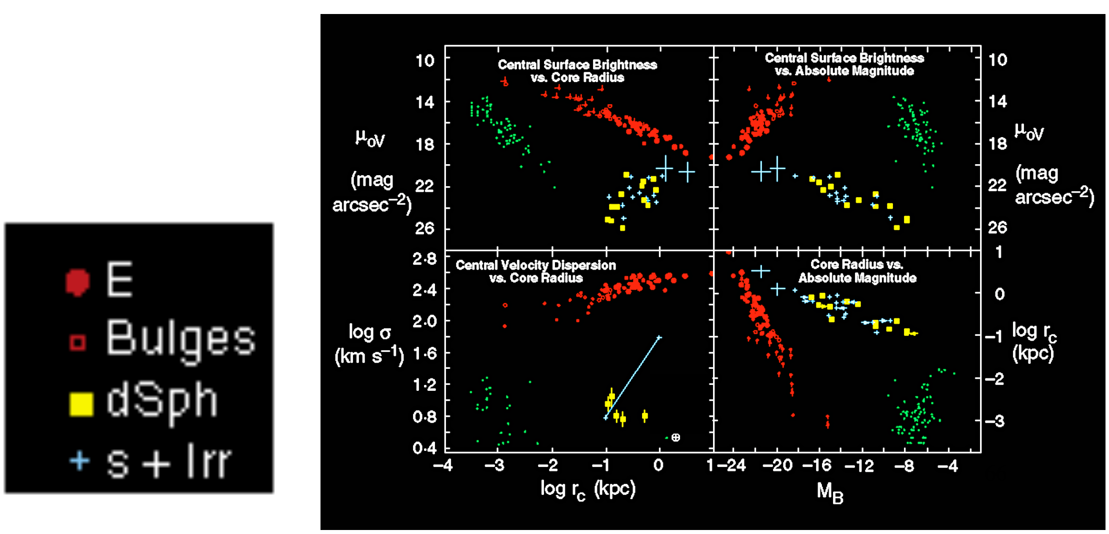
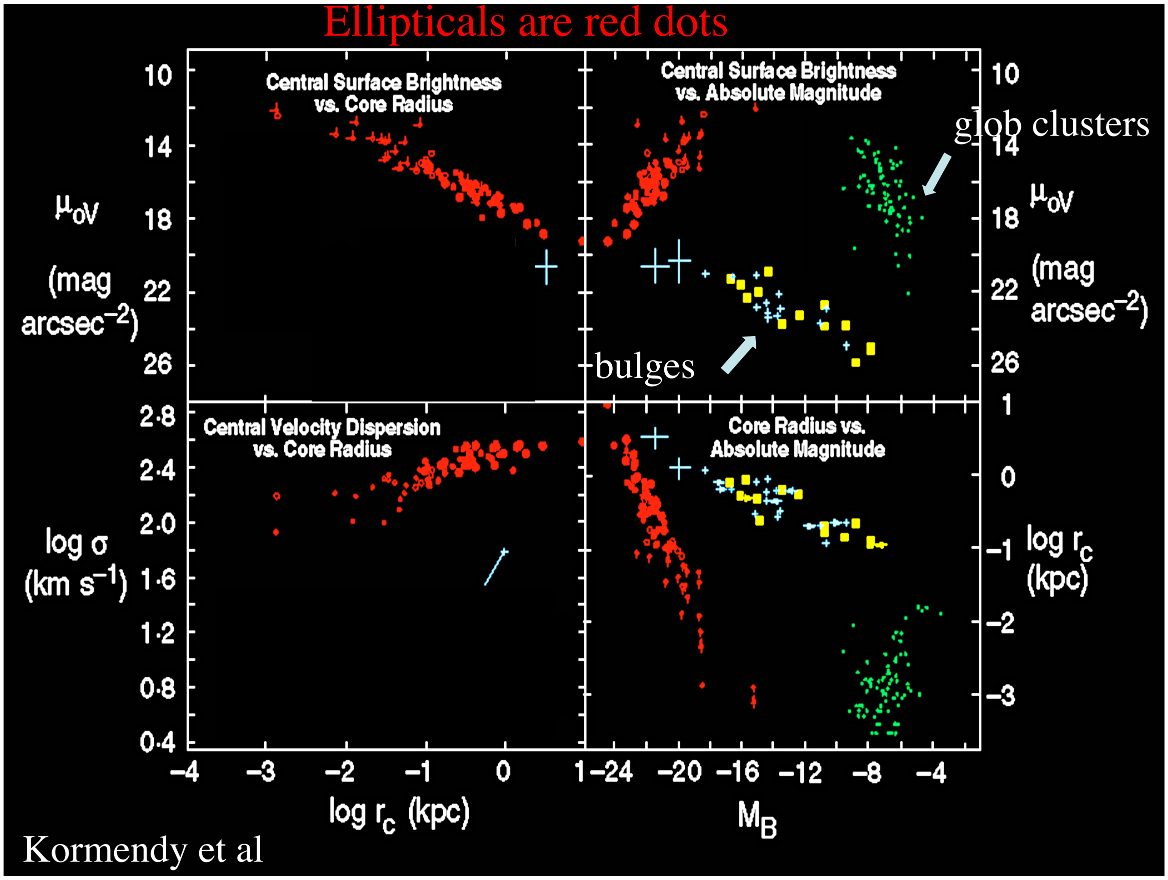
- 3 of the key observables of elliptical galaxies,
- the effective radius R_e, the central velocity dispersion σ, and the luminosity L (or equivalently the effective surface brightness $I_e = L/2\pi R^2_e$) relate their structural/ dynamical status to their stellar content.
- elliptical galaxies are *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 (σ,$L = 2\pi I_e R^2_e$) plane generates the Faber-Jackson relation (Faber & Jackson 1976).





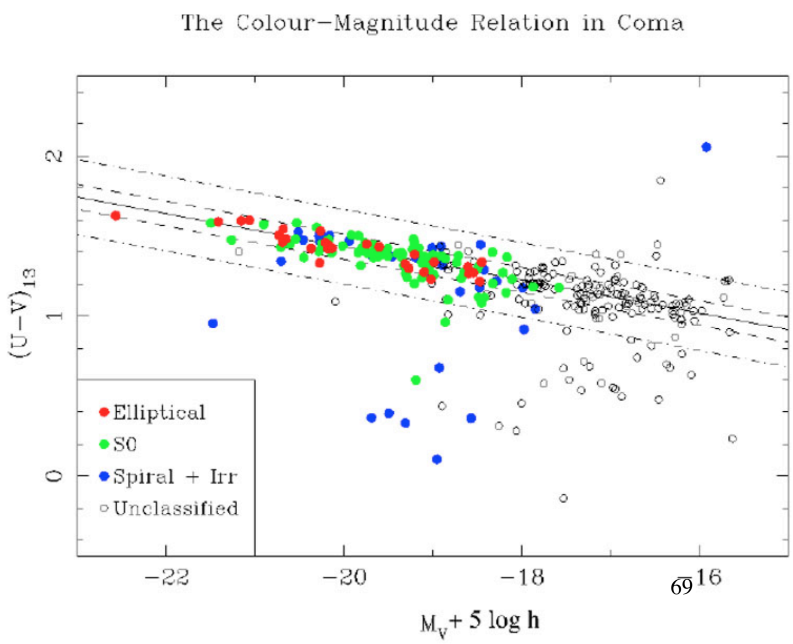
What Does Fundamental Plane Tell US

- 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.

Color Magnitude relation

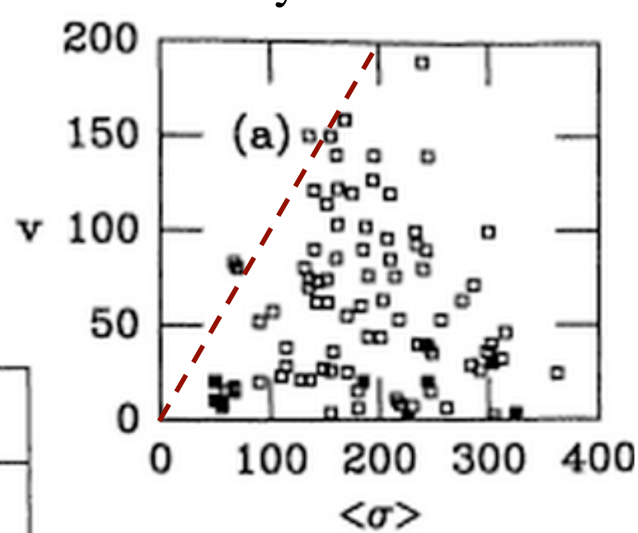
- Colors of elliptical galaxies strongly connected to their luminosity and have only a narrow range at almost all redshifts

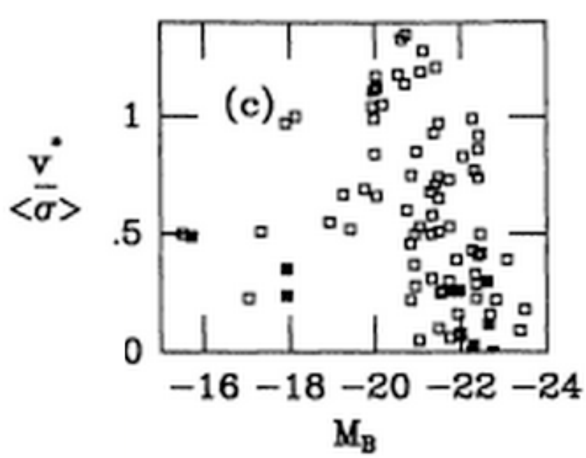
- So in a galaxy survey can pick out ellipticals and estimate their redshifts from 2 color photometry



Massive Ellipticals Rotate Slowly if at ALL

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





de Zeeuw and Franx 1991

shape primarily not due to rotation

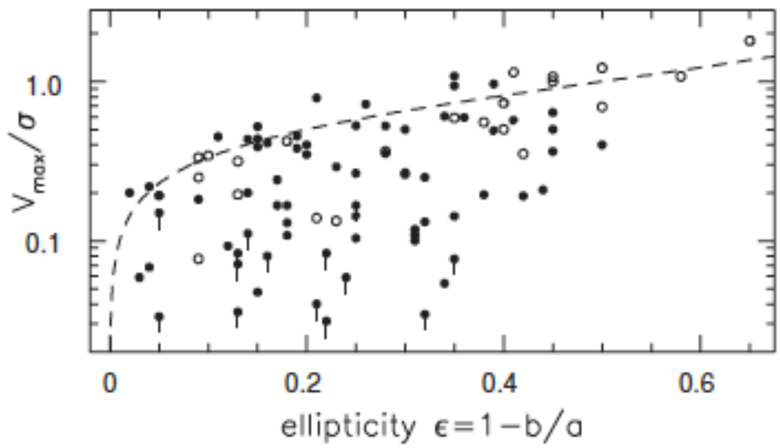


Fig 6.14 S&G

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

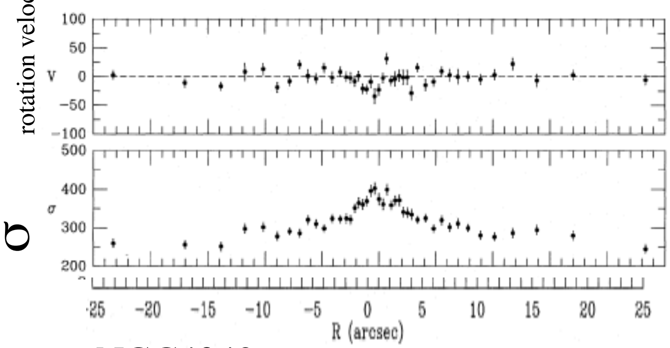
Narrow range of colors and mass vs indicates ages , metallicity and shape of the potential fall in a narrow pattern

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

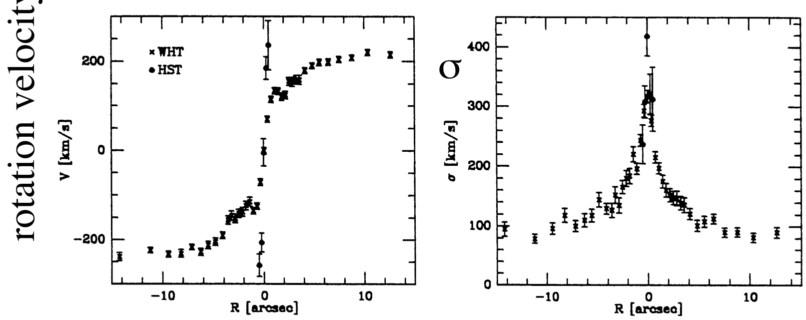
Kinematics

- 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

M87 van der Maerl



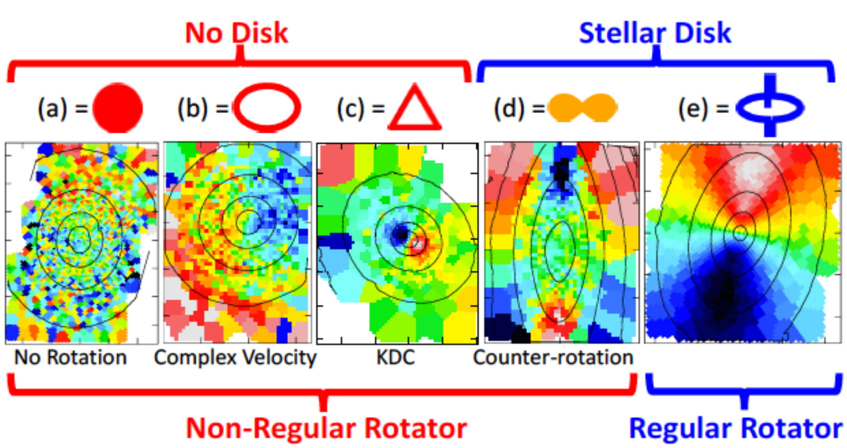
NGC4342
van den Bosch



For NGC4342 its observed flattening is consistent with rotation

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 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 shift: red/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 Σ (x_{proj}),Σ(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 $t_{dynamical}$ ~ 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

$(1/\rho)d(\rho<v_r>^2)/dr+2\beta/r<v_r>^2=-d\phi/dr$

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 !

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

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

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

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

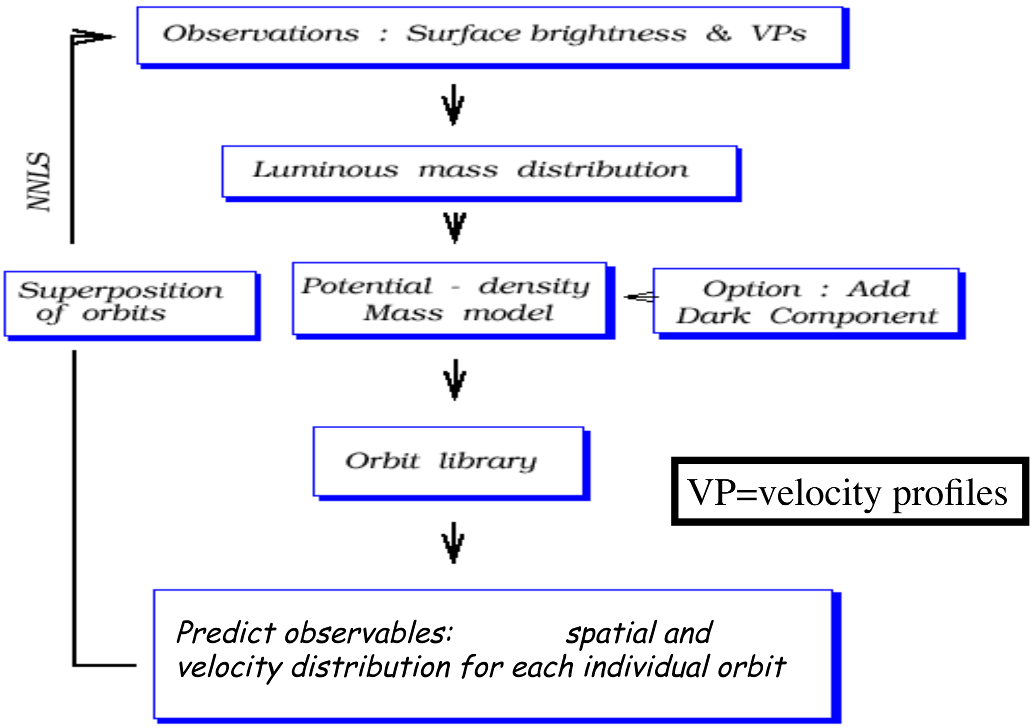
- $\beta= 1,0,-\infty$ radial, isotropic, and circular orbits, respectively

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

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



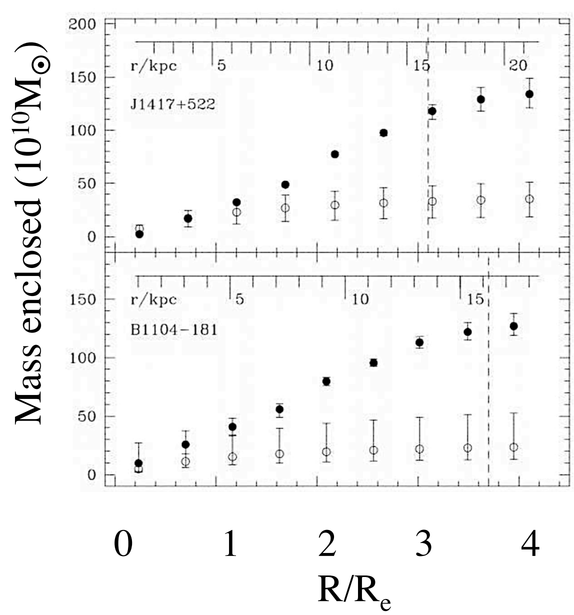
Degeneracies

- 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

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

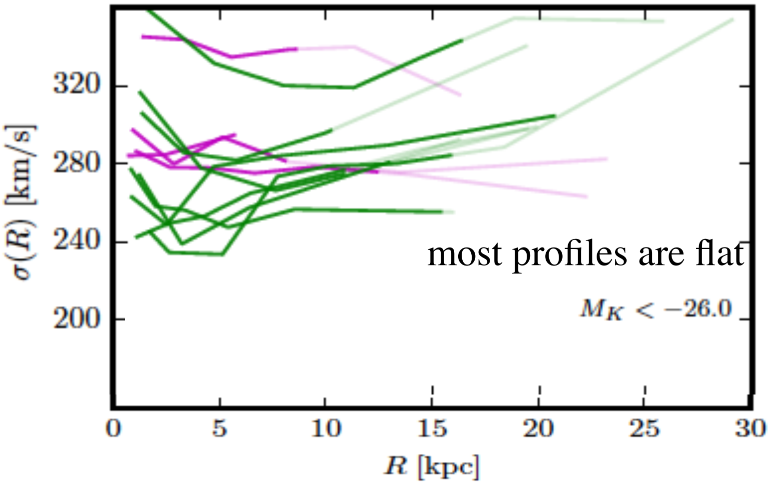


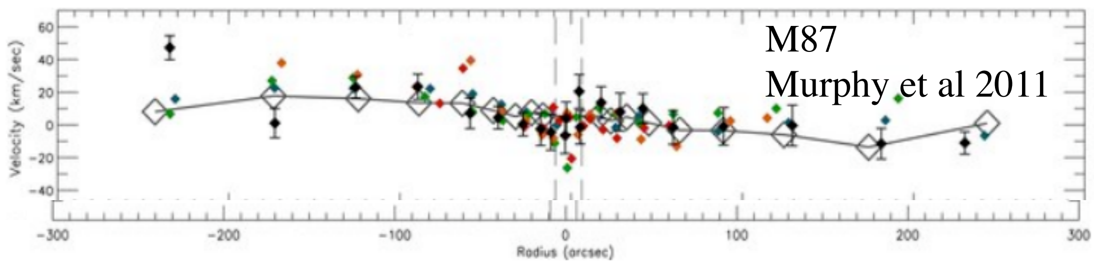
black points total mass, *open points stellar mass for two lensed galaxies* (difference is Dark matter)

Ferreras , Saha and Williams 2005

New Data

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

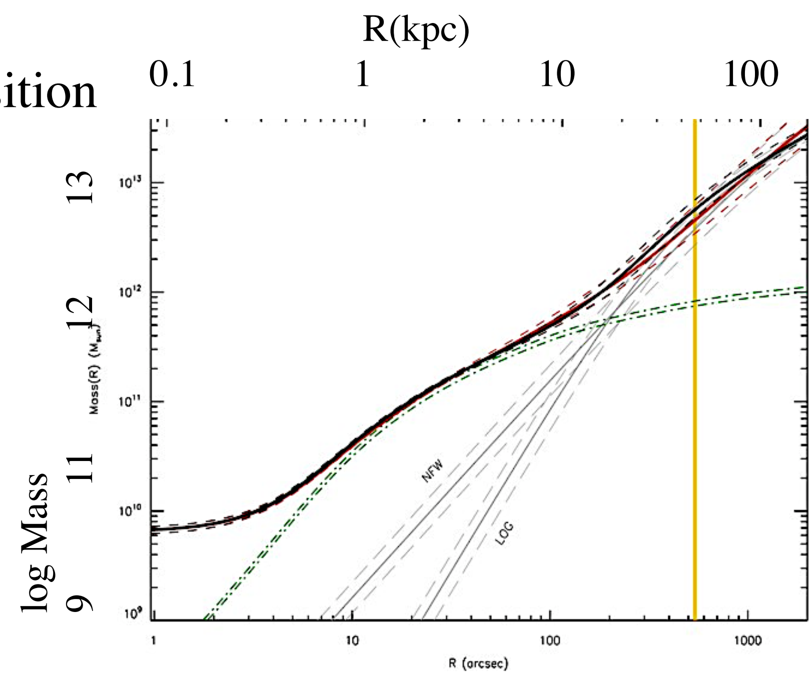




100"=7.8kpc

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)

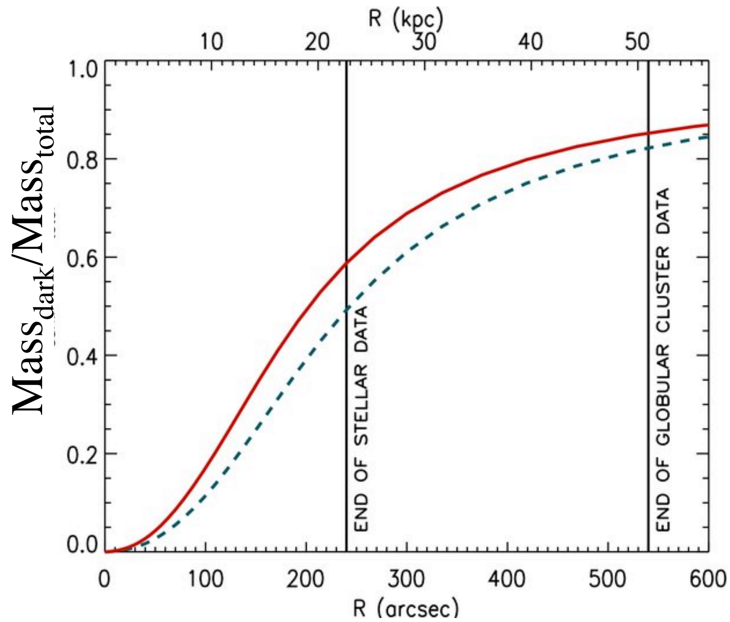


Black= total mass
Green= stellar mass

Dark Matter Dominates at Large Radii

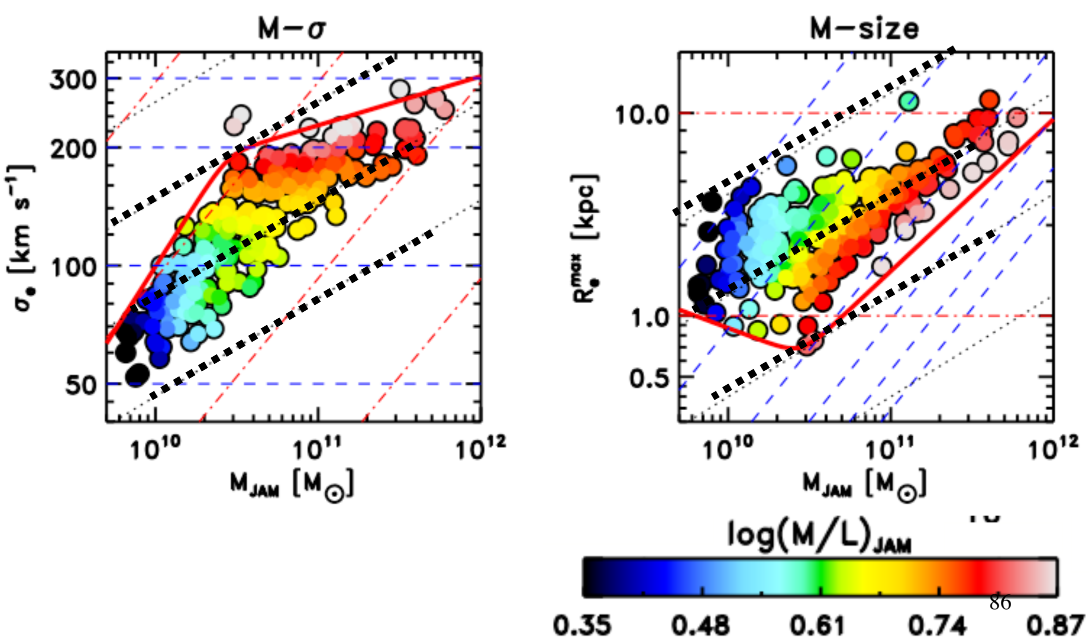
- Murphy et al 2011 M87 data
- for more material see **Structure and Kinematics of Early-Type Galaxies from Integral-Field Spectroscopy**

Michele Cappellari
arXiv:1602.04267



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- 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.

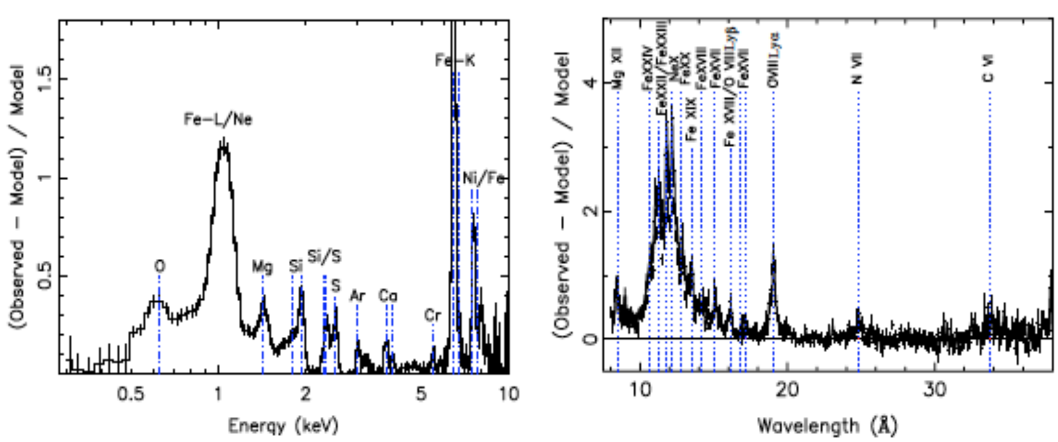


Fig. 31 *Left panel* The line spectrum of the cluster 2A 0335+096, as observed with *XMM-Newton* EPIC

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

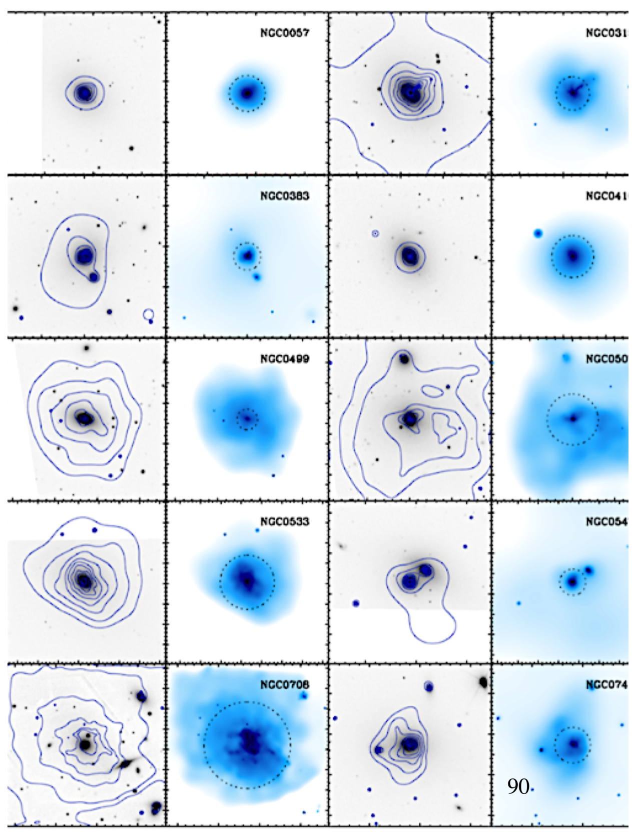
The temperature T_g from the spatially resolved spectrum

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

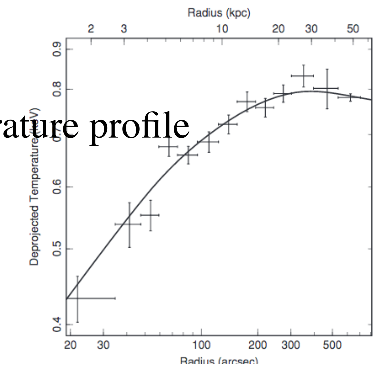
And the scale size, **r**, from the conversion of angles to distance

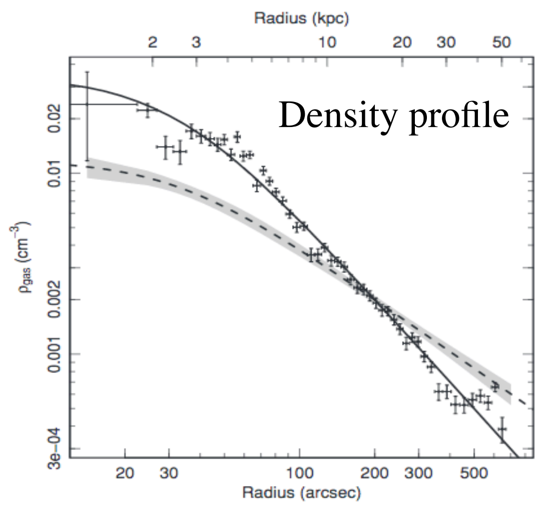
X-rays Extend to Large Radii

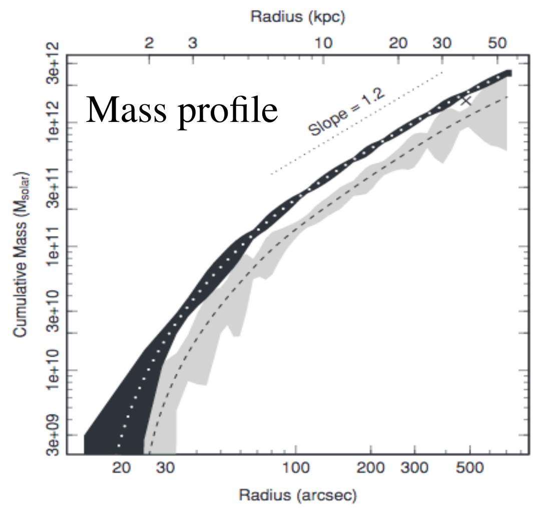
- X-ray and optical images of elliptical galaxies (Goudling et al 2016)
  - (dotted circle is R_e)



Use of the Data





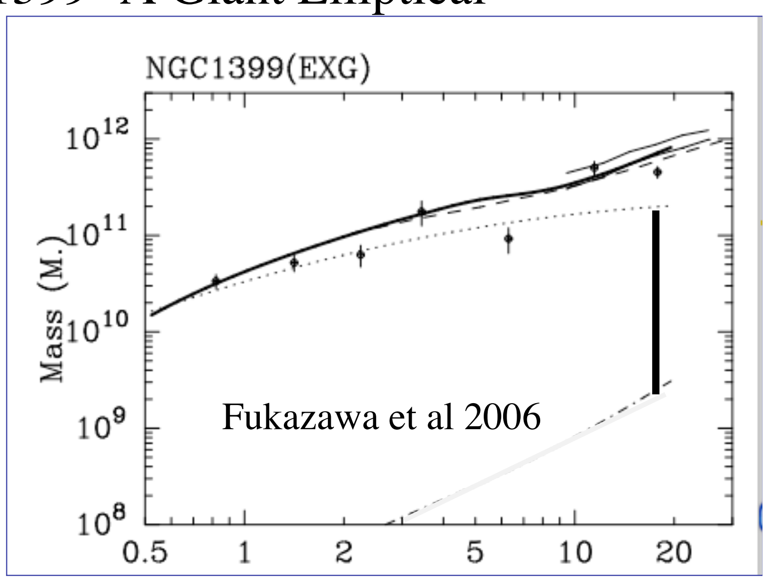


NGC1399- A Giant Elliptical

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)



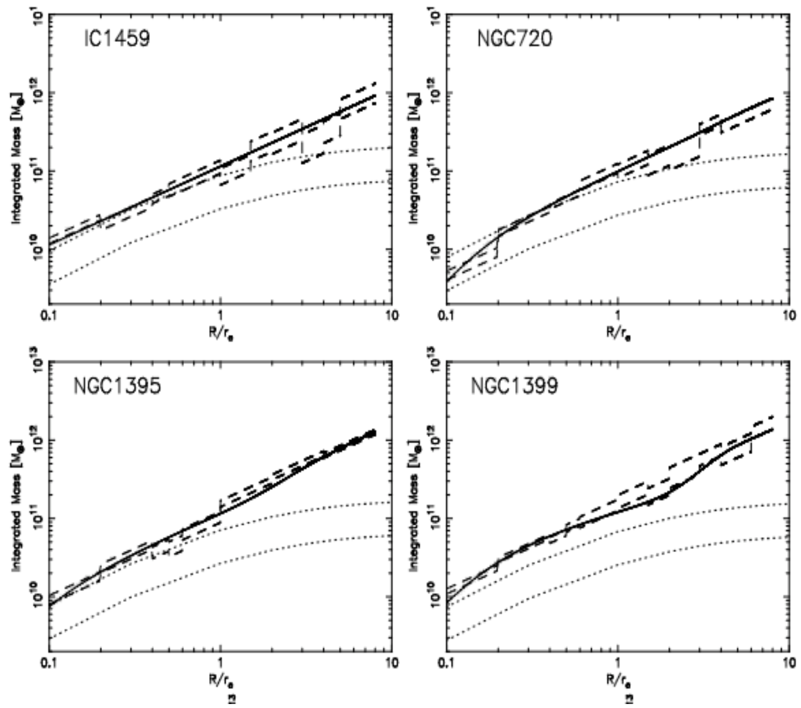
•Use hydrostatic equilibrium to determine mass

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

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

Masses from X-ray Data

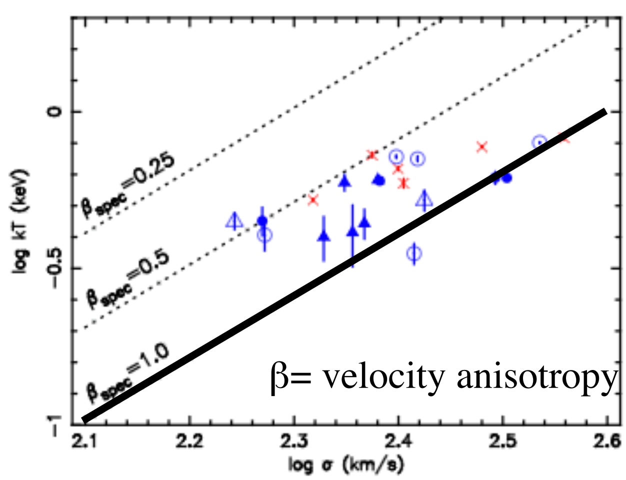
- Frequently can determine mass at r>>R_e
- Dark matter dominates at r>>R_e



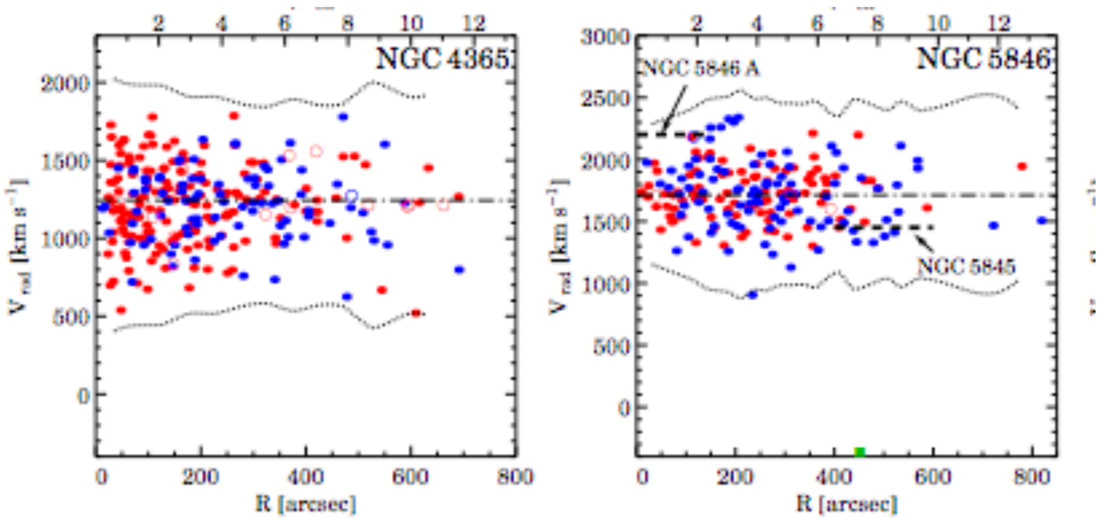
Nagino and Matsushita 2009

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



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