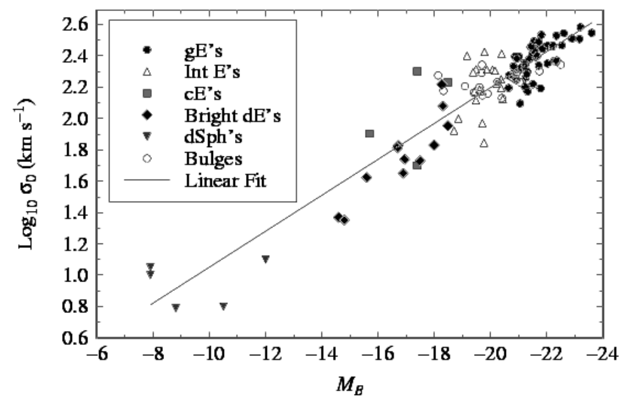
Faber-Jackson relation:

- In 1976, Faber & Jackson found that:
  - Roughly, $L \propto \sigma^4$
  - More luminous galaxies have deeper potentials
  - Can show that this follows from the Virial Theorem
  - Why is this relationship useful??
  - There is a large scatter – a second parameter?

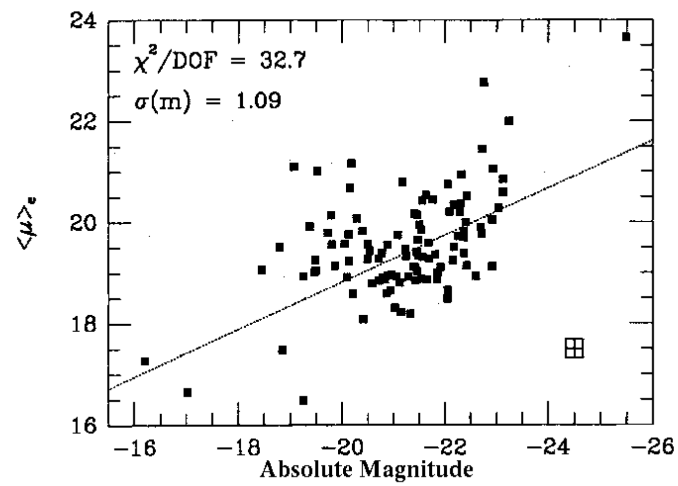
Faber-Jackson Relation



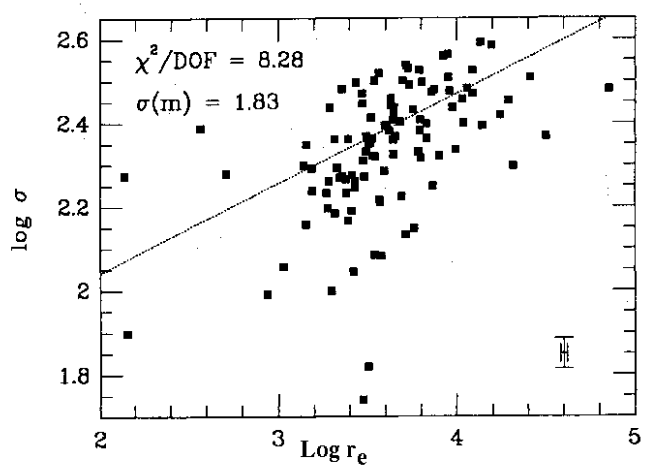
Fundamental Plane:

- The missing parameter is effective radius (discovered in 1987). There are four observables (but only 3 independent parameters):
  - Luminosity
  - Effective radius
  - Mean surface brightness
  - Velocity dispersion
- You can fit a FUNDAMENTAL PLANE through the observables
  - $r_e \propto \sigma^{1.24} \langle I \rangle^{-0.82}$
- Any model of galaxy formation has to reproduce this relation
- Can also define the D_n-σ relation for use as a distance indicator

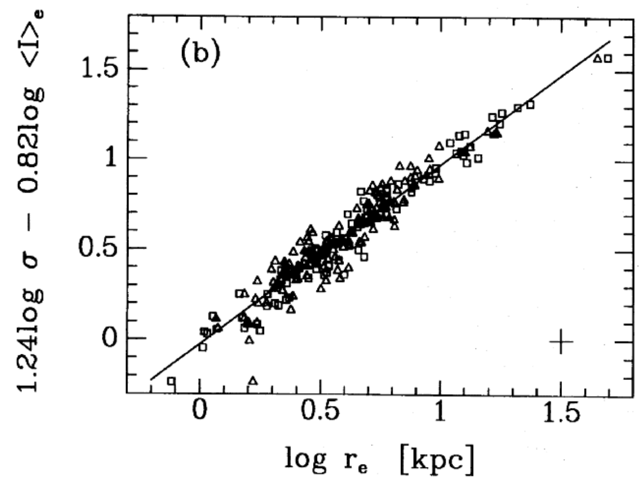
Surface brightness vs. luminosity



Velocity dispersion vs. effective radius



Fundamental Plane



Stellar Populations:

- In 1944, Walter Baade used the 100 inch Mt. Wilson telescope to resolve the stars in several nearby galaxies: M31, its companions M32 and NGC 205, as well as the elliptical galaxies NGC 147 and NGC 145
- Realized the stellar populations of spiral and elliptical galaxies were distinct:
  - Population I: objects closely associated with spiral arms – luminous, young hot stars (O and B), Cepheid variables, dust lanes, HII regions, open clusters, metal-rich
  - Population II: objects found in spheroidal components of galaxies (bulge of spiral galaxies, ellipticals) – older, redder stars (red giants), metal-poor

Stellar Populations of Ellipticals

- Ellipticals are full of old, red stars
- Ellipticals follow a color-magnitude relation such that more luminous galaxies are redder
  - Is this due to age or metallicity?
- Age/metallicity degeneracy!!

Typical Elliptical galaxy spectrum

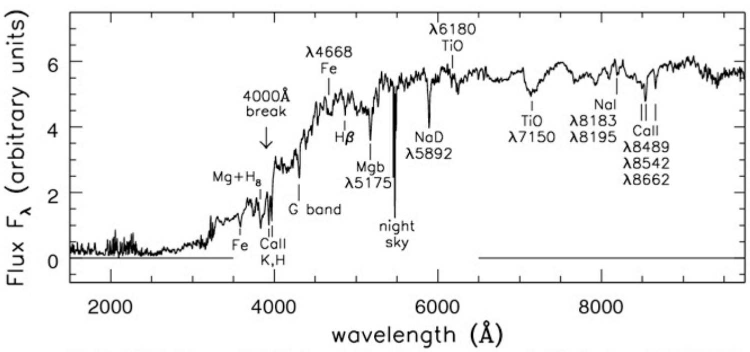


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Evolution of a single burst population

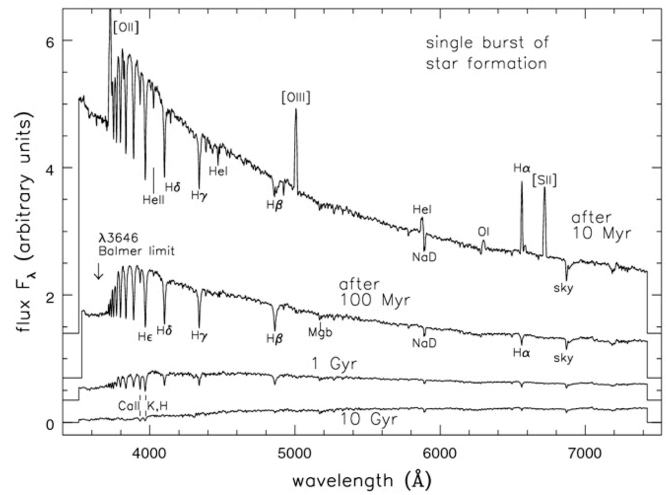
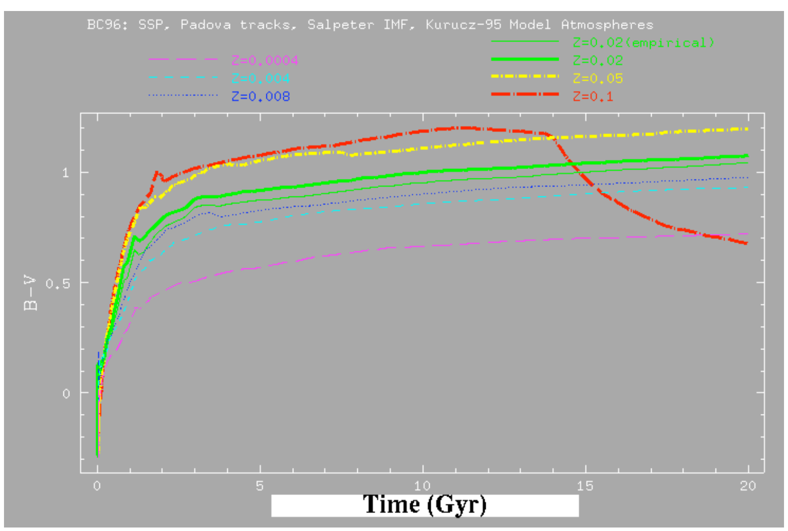


Fig 6.18 (B. Poggianti) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

B-V for different metallicity populations



Stellar Populations of Ellipticals

- There is also a strong correlation between Mg_2 and velocity dispersion such that galaxies with higher velocity dispersions have stronger Mg_2 absorption
- Thus, more luminous/massive galaxies are more *metal rich* -- deeper potentials hold ISM longer allowing metals to build up
- There are also color & abundance gradients in elliptical galaxies

Color luminosity relation

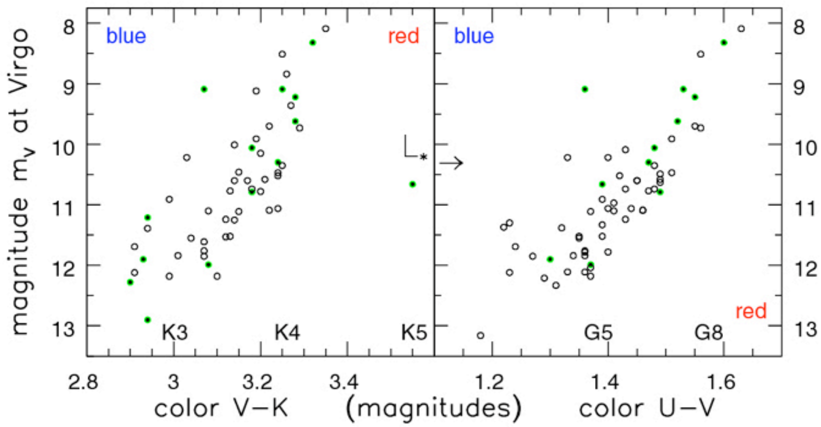
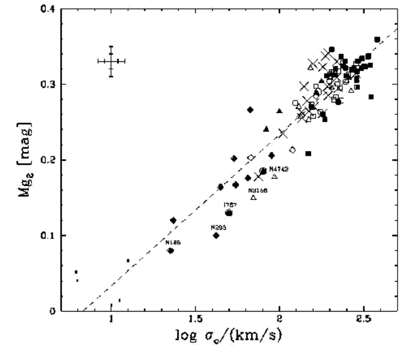


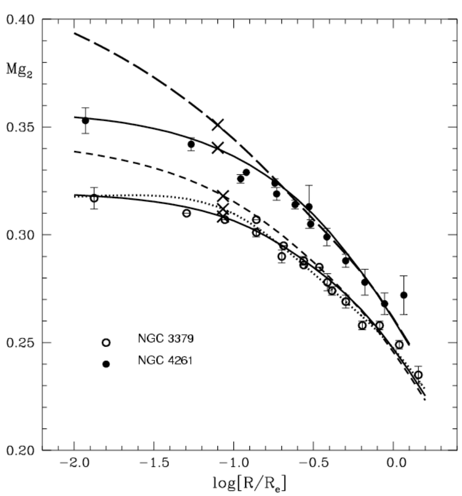
Fig 6.19 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Mg2 vs velocity dispersion

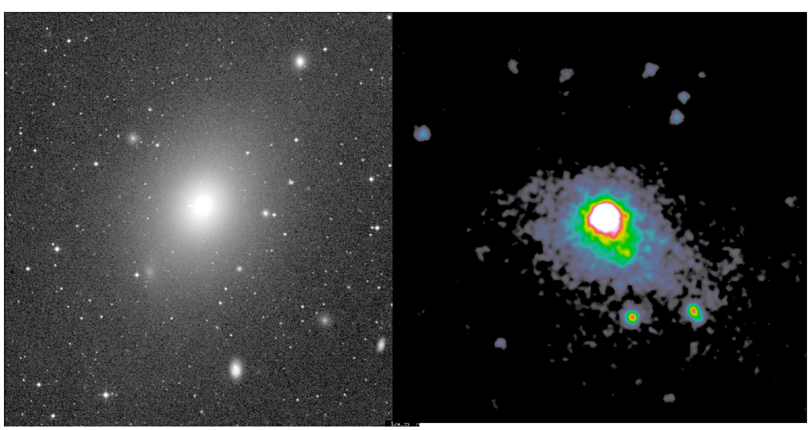


Relationship between Mg_2 and σ_o for ellipticals (squares), S0 bulges (crosses), dwarf ellipticals (diamonds and small squares), special objects (open squares).
(Bender, IAU Symp 149)

Abundance gradients in ellipticals



Many ellipticals have extended x-ray halos of gas



Optical M49 X-ray

Hot Gas in Ellipticals

- Many ellipticals have extended x-ray halos of gas. $T \sim 10^6$ K
- Where does it come from?
- Why is it hot?

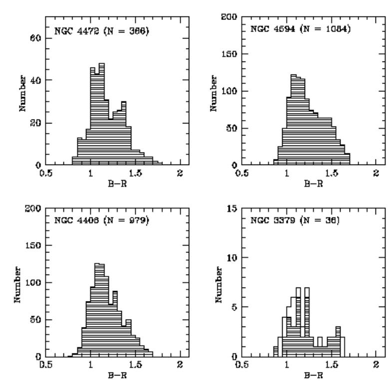
Hot Gas in Ellipticals

- Many ellipticals have extended x-ray halos of gas
- Where does it come from?
  - Mass loss of AGB stars!
- Why is it hot?
  - Motions of stars heat the gas:
    - $1/2 m\sigma^2 \sim 3/2\ kT$
    - $T = 10^6$ K !!!
    - M (gas) $\sim 10^8 - 10^9\ M_\odot$

Globular clusters in Ellipticals

- Ellipticals are surrounded by numerous globular clusters (about twice as many as a similarly luminous spiral)
- Globular cluster colors in ellipticals show a bimodal distribution
- This is probably a metallicity effect, so there is a population of metal poor and a population of metal rich GCs
- What does this mean?

Globular cluster color distributions



E2

S0

E3

E5

Rhode & Zepf 2004

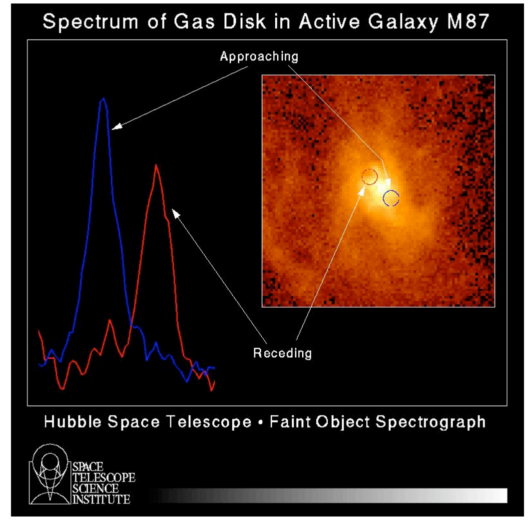
Fig. 9.— $B-R$ distributions for the early-type galaxy sample, including NGC 4472 from Paper I. For NGC 3379, the 36-object sample used to estimate the blue/red GC proportions is shown as a shaded histogram and the 50-object sample used as input to KMM is plotted with a solid line.

B-R color

Globular clusters in Ellipticals

- Globular cluster colors have implications for formation process:
- Either
  - – Merger of two galaxies – metal poor clusters are old, metal rich clusters formed during merger process
  - – Hierarchical formation – metal rich population builds up during accretion of gas rich clumps

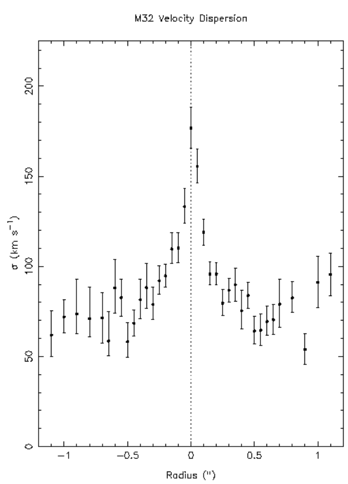
Many (all?) ellipticals (& bulges) have black holes



First direct detection – Ford et al (1994)

Many (all?) ellipticals (& bulges) have black holes- even compact ones like M32!

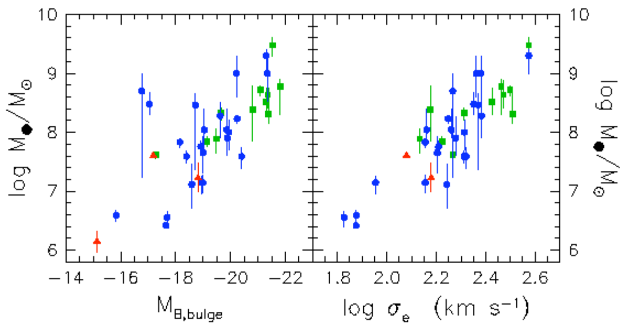
Can measure BH masses for galaxies without central disks via their velocity dispersion



Black holes

- Currently there are observations of at least 40 BH masses in nearby ellipticals and spiral bulges
- There is a strong correlation between black hole mass and galaxy luminosity and velocity dispersion

Black hole mass vs. galaxy luminosity & velocity dispersion



From Kormendy (2003) review

Black hole formation

- Observations imply BH mass directly tied to the formation of bulges and ellipticals
- Either
  - All proto-galaxy clumps harbored an equal sized (relative to total mass) BH, and BH merged as galaxy formed
  - BH started out small and grew as galaxy formed – e.g., central BH is fed during process of formation and is the seed of the formation process (all galaxies have BHs?)

Dark matter in elliptical galaxies

- Expected mass to light ratio of the stellar population implies M/L_V ~ 3-5
- Orbital motions of the stars in the centers of ellipticals imply they are not dark matter dominated
- In those (few!) ellipticals containing cold gas, we can measure the circular orbits of the gas we find M/L ~ 10 –20
  - But are these galaxies typical??
- Also can use the amount of mass required to retain the hot x-ray gas, find M/L~100 for galaxies with large x-ray halos
  - Are these typical?

Dark matter in elliptical galaxies

- Need a tracer particle that can be easily measured kinematically at large galactic radii
  - 2 possibilities – globular clusters and planetary nebulae
  - Recent results of PN dynamics around (a few) elliptical galaxies show NO dark matter, the galaxies are "naked"
  - Recent results of GC dynamics around (a few) elliptical galaxies show large dark halo. Are we measuring the galaxy potential or the potential of the cluster it lives in??

Planetary nebulae dynamics

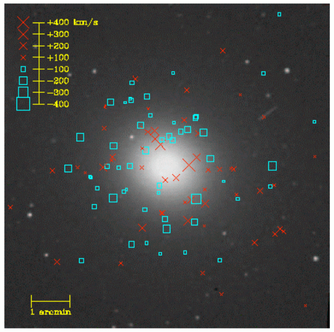


Fig. 1. NGC 3379 with 109 PN line-of-sight velocities relative to the systemic velocity, as measured with the 4.2-m William Herschel Telescope and the PN.S instrument. The symbol sizes are proportional to the velocity magnitudes. Red crosses indicate receding velocities; blue boxes, approaching velocities. The background image is from the Digitized *Sky Survey* (*35*), and the field of view is $8'.4 \times 8'.4 = 26 \times 26$ kpc $= 14 \times 14\ R_{\rm eff}$.

Romanowsky et al. 2003

Planetary nebulae dynamics

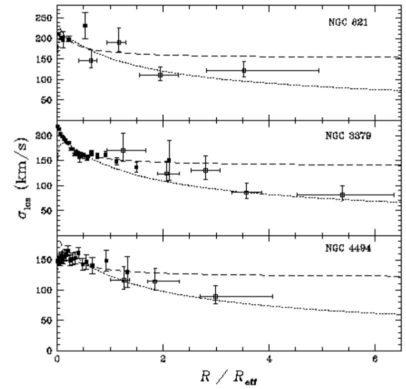


Fig. 4. Line-of-sight velocity dispersion profiles for three elliptical galaxies, as a function of projected radius in units of $R_{\rm eff}$. Open points show planetary nebula data (from the PN.*S*); solid points show diffuse stellar data (*11–13*). The vertical error bars show 1 σ uncertainties in the dispersion, and the horizontal error bars show the radial range covered by 68% of the points in each bin. Predictions of simple isotropic models are also shown for comparison: a singular isothermal halo (dashed lines) and a constant mass-to-light ratio galaxy (dotted lines).

Romanowsky et al. 2003