# Astronomy 330

Lecture 18

10 Nov 2010

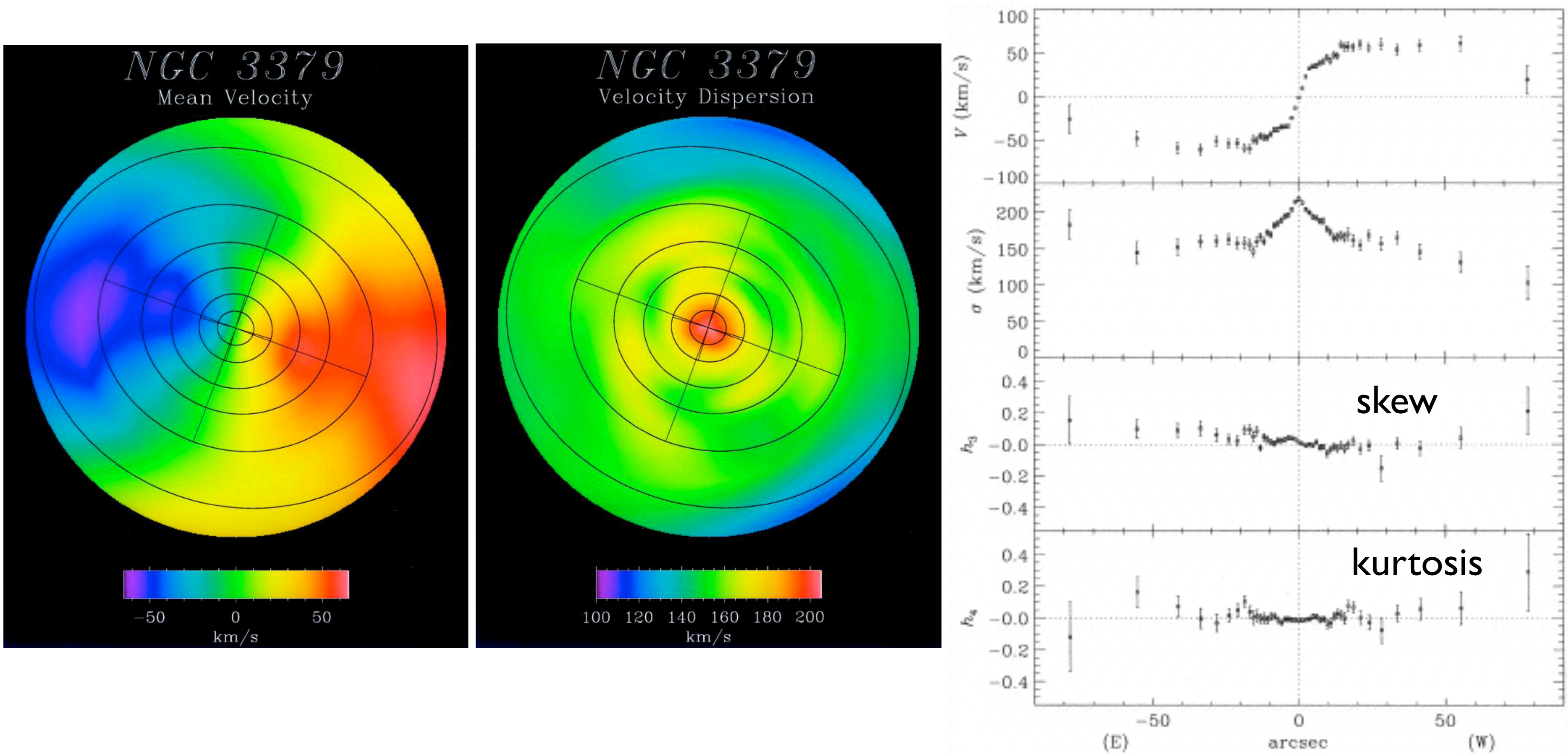
# Outline

- Review:
  - Elliptical galaxies
    - Basic properties
- Internal structure
- Formation

# Ellipticals: Basic properties

- Surface photometry
  - Well-described by a Sersic profile of index $3<n<10$.
    - n=4 is the classic "r1/4" law proposed by de Vaucouleurs
  - Flattening: E0-E7 describes b/a
  - Distinct distribution of size, luminosity and surface-brightness
    - see Figure 6.6 in S&G (we'll come back to this in a moment)
- Stellar populations: old, metal rich
- Gas content:
  - little cold, cool, or warm gas; considerable hot (x-ray) gas
- Environment: dense, usually in clusters or rich groups
  - morphology-density relationship

# Elliptical galaxies do rotate …




- … it's just that their dispersion is larger.

# True shape of elliptical galaxies

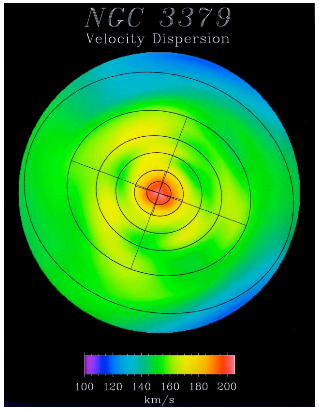
- We see the 2-dimensional projection of a three dimensional thing: How can we tell the true shape?
  - Prolate or oblate?
    - Orbits
    - Viewing angle
    - Velocity fields
- Look for deviations in the 2-dimensional data ➔ twists in the isophotes
  - Peng, Ford, Freeman (2004) use planetary nebula to map kinematics in NGC 5128
  - PNs ➔ bright, emission line sources, widely distributed
  - 1141 PNe ➔ velocity field for N5128
  - Twist in isovelocity contours suggests triaxiality
- Can do this with stellar velocity fields within the galaxy as well (see papers by Statler et al)

# Scaling relations: The so-called "Fundamental Plane"

- Scaling relationship between size, velocity dispersion, and surface-brightness
  - Faber-Jackson law: $L \sim \sigma^4$
- E's occupy a plane in $R_e$, $\sigma$, $\mu_e$ space
  - $R_e \sim \sigma^A \mu^B$
    - A ~1.4
    - B ~-0.8
- Virial theorem:
  - $\langle R_e \rangle = \langle \sigma^2 \rangle \langle I_e \rangle^{-1} \langle M/L \rangle^{-1}$
- Observed fit:
  - $\log R_e = -0.8 \log I_e + 1.4 \log \sigma$
- Why the discrepancy?
  - M/L is not constant?
  - E's have anisotropic velocities?

$R_e$: the half-light radius
$\sigma$: the velocity dispersion
$\mu_e$: the surface-brightness at $R_e$ (mag $arcsec^{-2}$)
$I_e$: the surface-brightness at $R_e$ in flux units.

*Question*: At what radius is $\sigma$ measured?
*Recall*:



# Fundamental Plane (2-D projections)

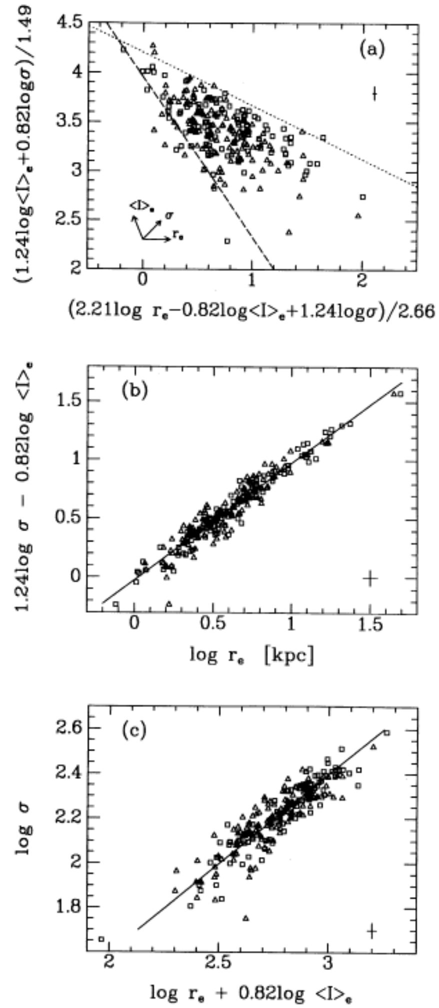
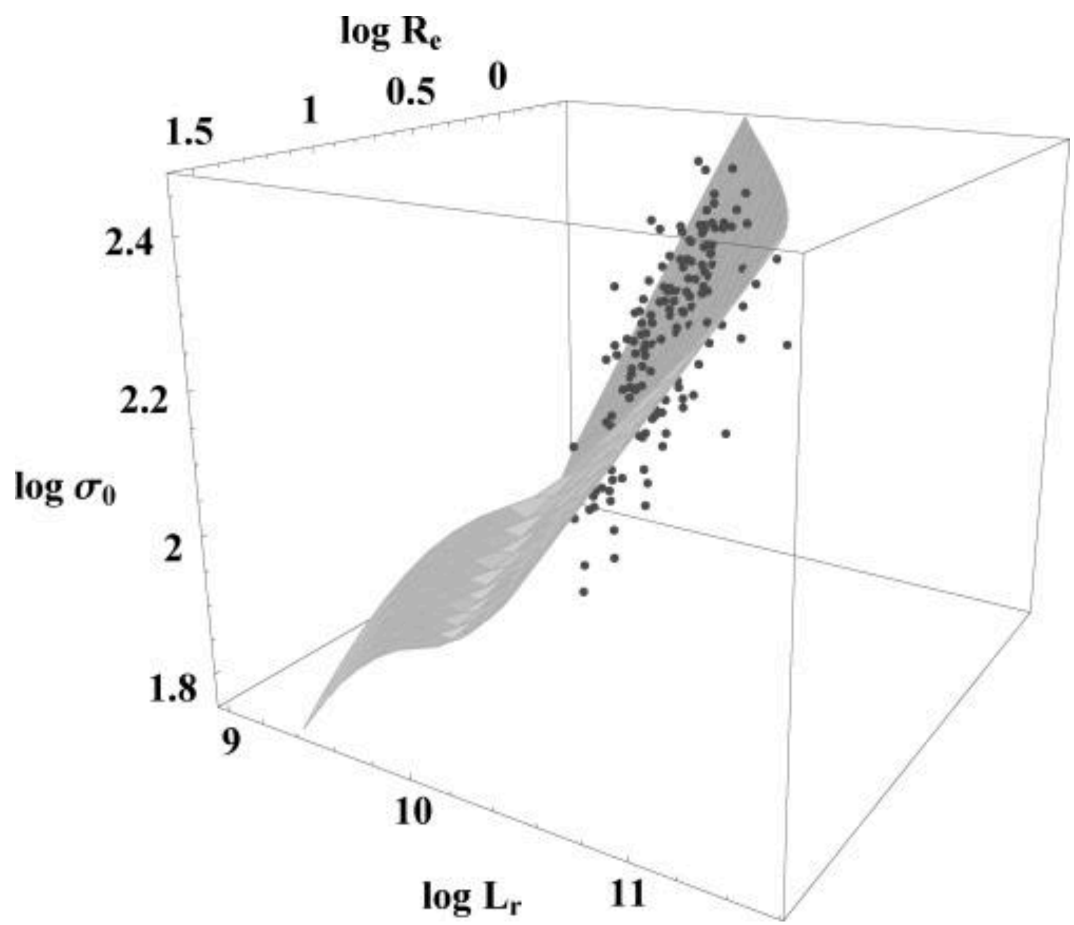



**Figure 1.** (a) The FP in Gunn *r* as derived in equation (1) shown face-on for all galaxies in the sample. The arrows in the lower left corner of the panel show in which directions the measured parameters increase. The dashed line shows the selection effect due to a limiting magnitude of −20.45 mag in Gunn *r*. This is the magnitude limit for the Coma cluster sample. The upper boundary (dotted line, $y \approx -0.54x + 4.2$) is not caused by selection effects. (b) The FP in Gunn *r* (equation 1) shown edge-on for all galaxies in the sample. This edge-on view is along one of the longest sides of the plane, the effective radius. (c) The FP in Gunn *r* (equation 1) shown edge-on along one of the shortest sides of the plane, the velocity dispersion. The effective radii have been derived in kiloparsec from the relative distances given in Table 4; $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ was used. Boxes, E galaxies; triangles, S0 galaxies. Typical error bars are given on the panels.



$$\log r_e = \underset{\pm 0.05}{1.35} \log \sigma - \underset{\pm 0.03}{0.82} \log \langle I \rangle_e + \gamma_{cl} \quad .$$

# Fundamental Plane (3-D)

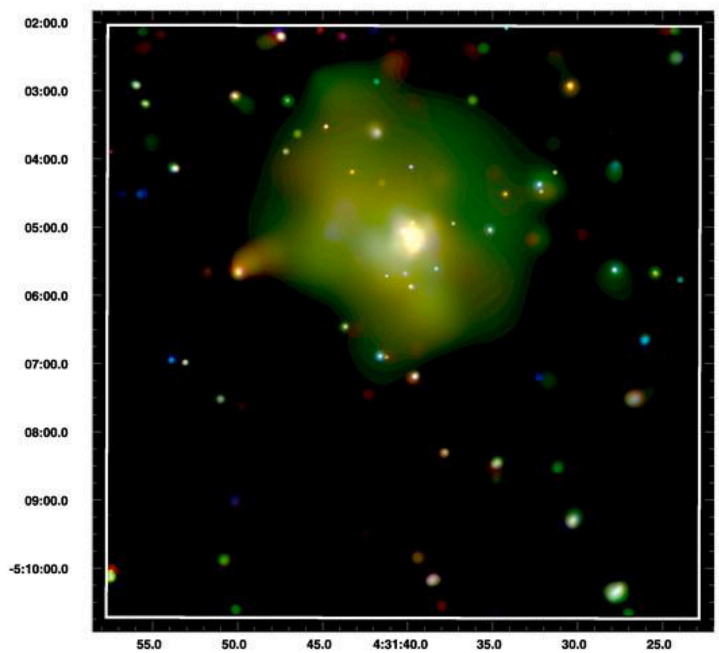


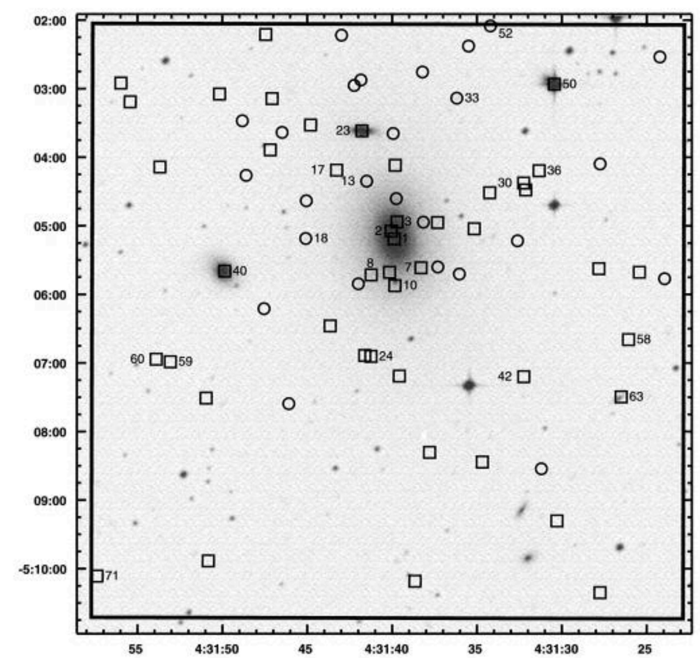
# Hot Gas and Dark Matter

- T ➔ velocity dispersion ➔ mass distribution
  - Let's assume hydrostatic equilibrium
    - pressure support balances gravitational potential
    - $dp/dr = -\rho\, GM(r)/r^2$
  - $d/dr(\rho_{gas}\, kT/\mu m_p) = -\rho_{gas}\, GM(r)/r^2$
    - μ here is the mean atomic mass
  - Direct measure of elliptical mass from X-ray data
  - Also works in galaxy clusters
- Gas temperature > stellar kinetic temperature
  - $\mu m_p \langle \sigma \rangle^2 / k \langle T \rangle \sim 0.5$
  - ➔ this alone suggest some dark matter
  - $T_{gas}/T_*$ ratio increases for low velocity dispersion
    - What does this tell us?

# X-ray to Optical comparison

- Recall:



# Stellar kinematics and dark matter

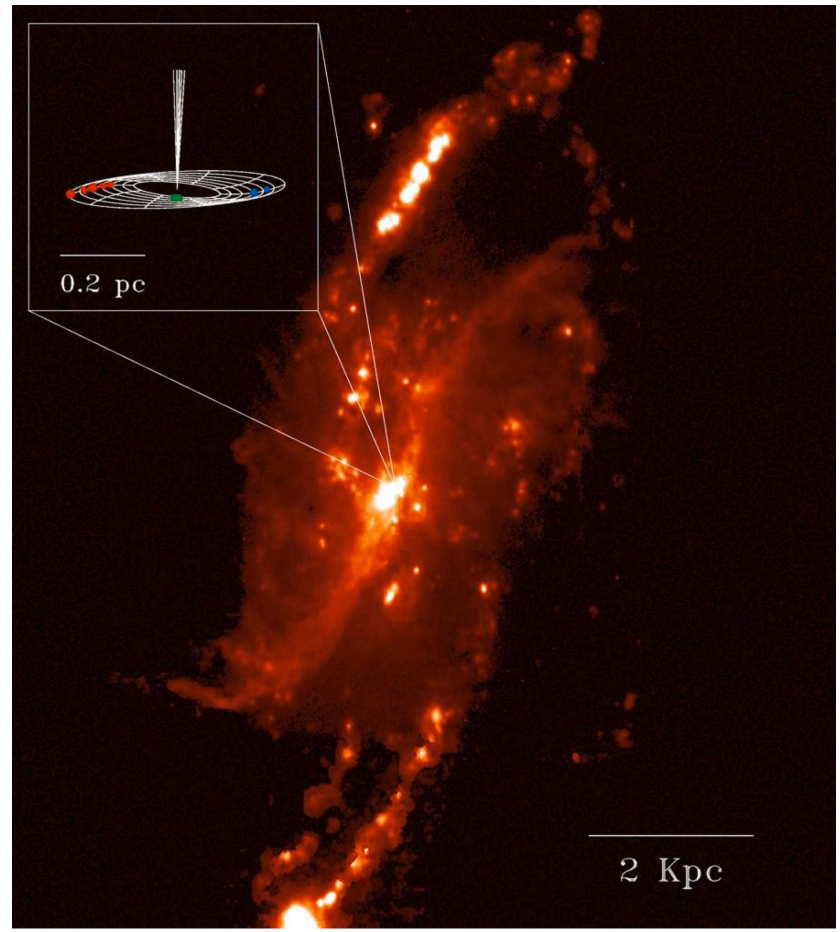
- Apply something like the CBE
- Jeans equation for spherical, isotropic stellar system
  - $d(\rho\ \sigma^2)/dr = -GM(r)\,\rho/r^2 + \rho V^2/r$
  - Adopt a mass model
    - e.g. isothermal sphere, NFW halo
      - This is only for the dark matter
    - e.g. Hernquist: $\rho(r) = (M_l a/2\pi)(1/r(r+a)^2)$
      - This is only for the luminous matter
  - For N5128, this yields M/L ~ 12-15

# Central regions

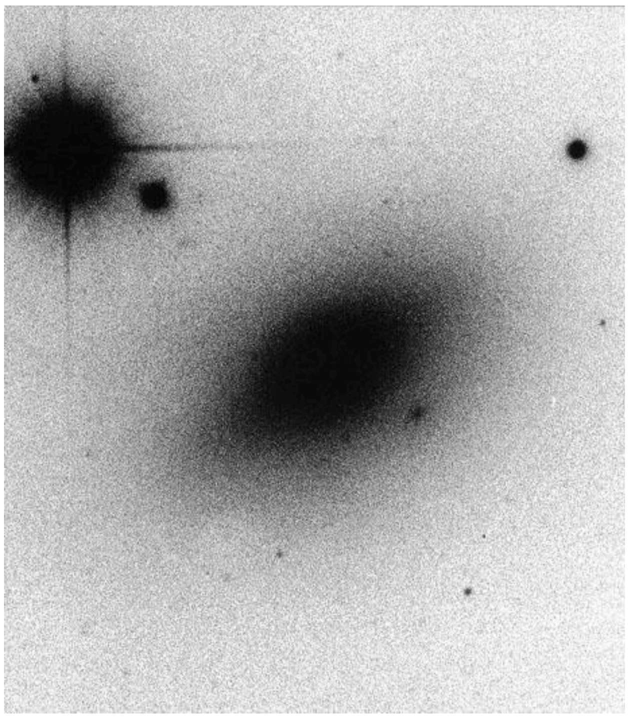
- Based on high-resolution photometry
  - try to fit some function to the observed light distribution
  - looking for deviations from Sersic profile
    - $I(r)=I_b 2^{(\beta-\gamma)/\alpha}(r_b/r)^{\gamma}[1+(r/r_b)^{\alpha}]^{(\gamma-\beta)/\alpha}$
      - $r_b$ = "break" radius
      - $\gamma$ = inner logarithmic slope ($r < r_b$) ➔ $\gamma = -d \log I / d \log r$
      - $\beta$ = outer slope
      - $\alpha$ = sharpness of break
- "core" galaxies ($\gamma > 0$)
- "power law" galaxies – steep surface brightness profile with luminosity densities in center brighter than "core" galaxies
  - tend to be less luminous, smaller galaxies
- Two families of early-type galaxies
  - Mergers/BH increase velocity dispersion and flatten light profile
  - Gas dissipation increases nuclear luminosity

# Central black holes

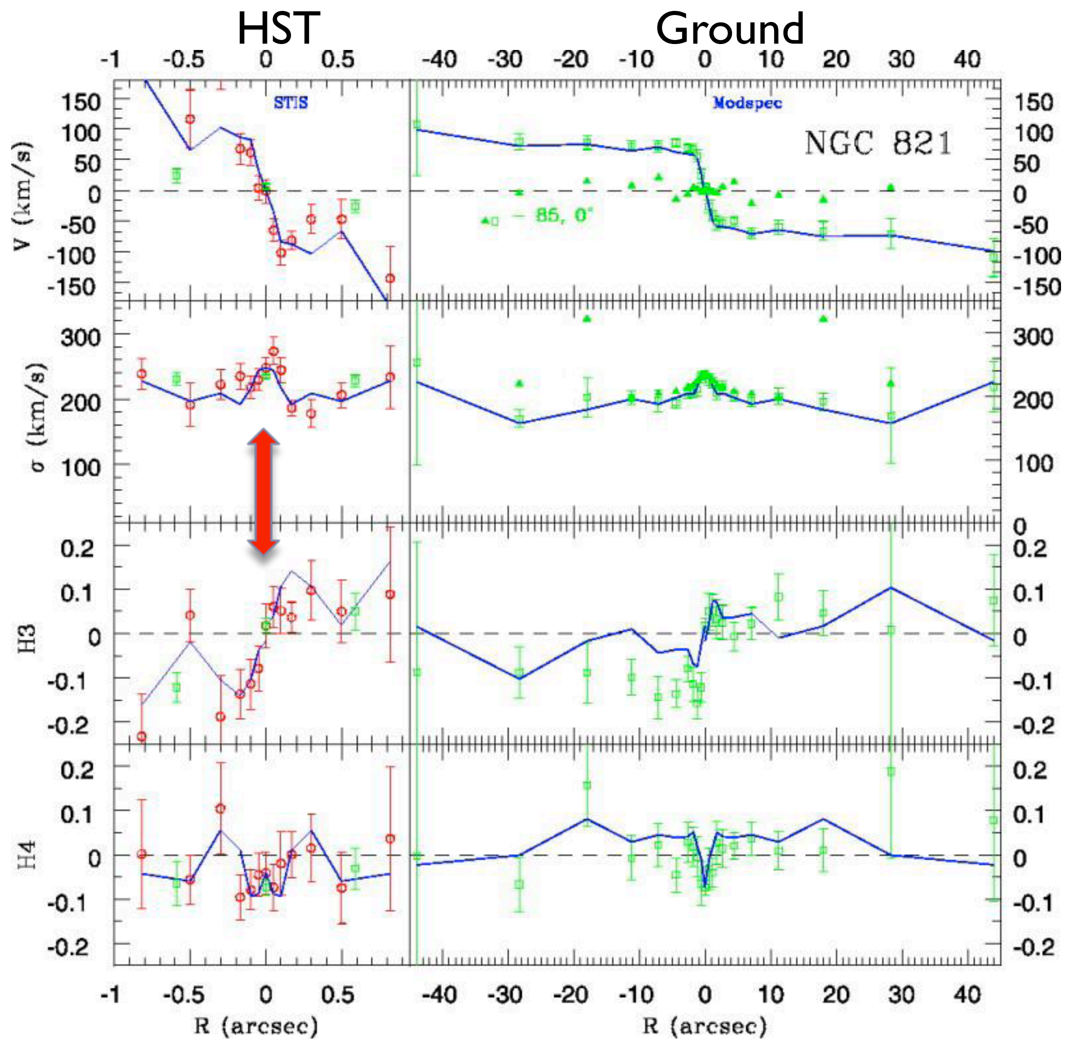
- How do you tell?
- Ellipticals
  - Central surface brightness
  - Velocity dispersions
  - $M_{BH}/\sigma$ relationship
- Spirals
  - Rotational velocities
  - VLBA measurement of masers in NGC 4258



# Case study: NGC 821

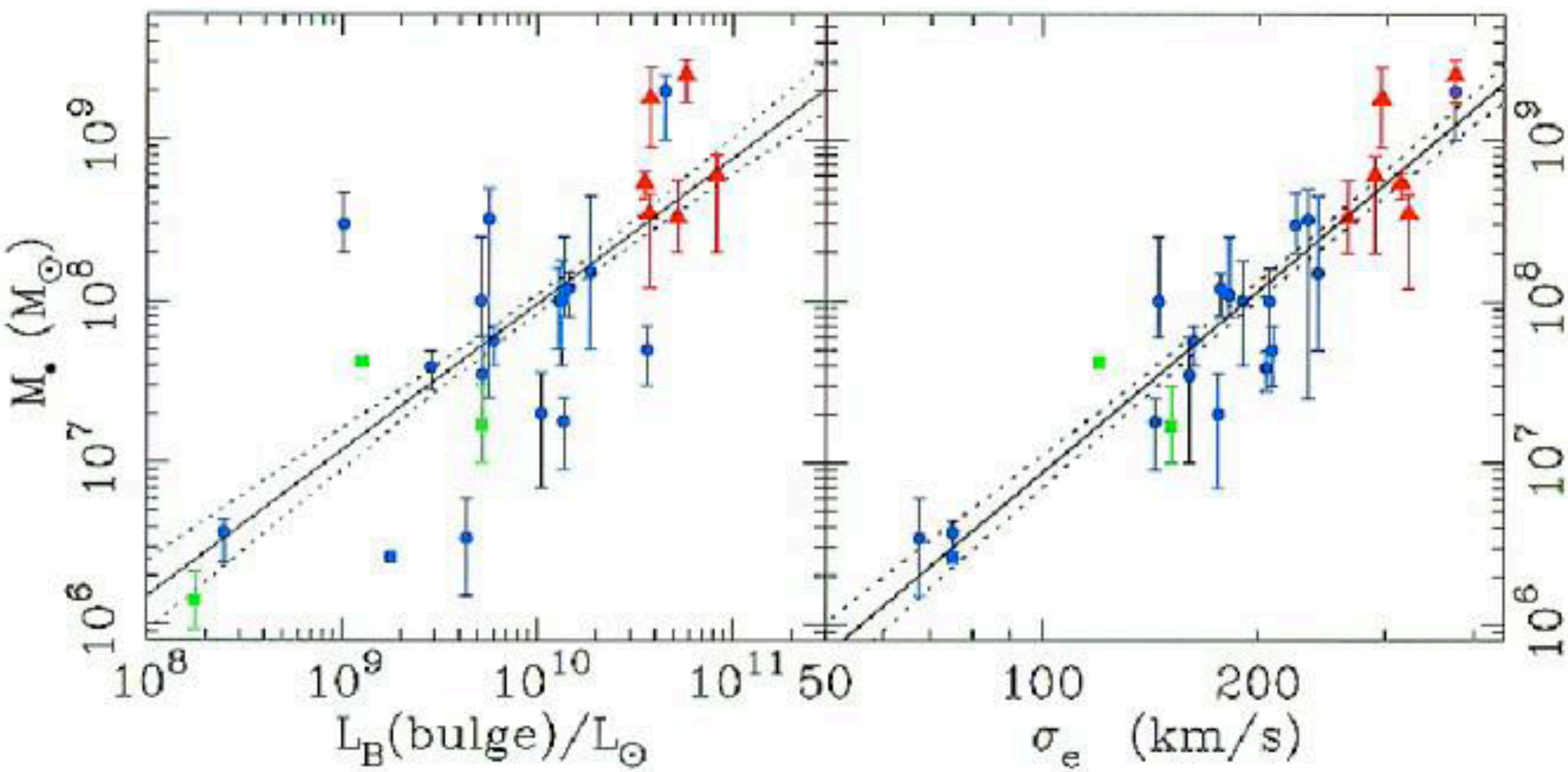


Ground-based image



# $M_{BH}/\sigma$ relationship

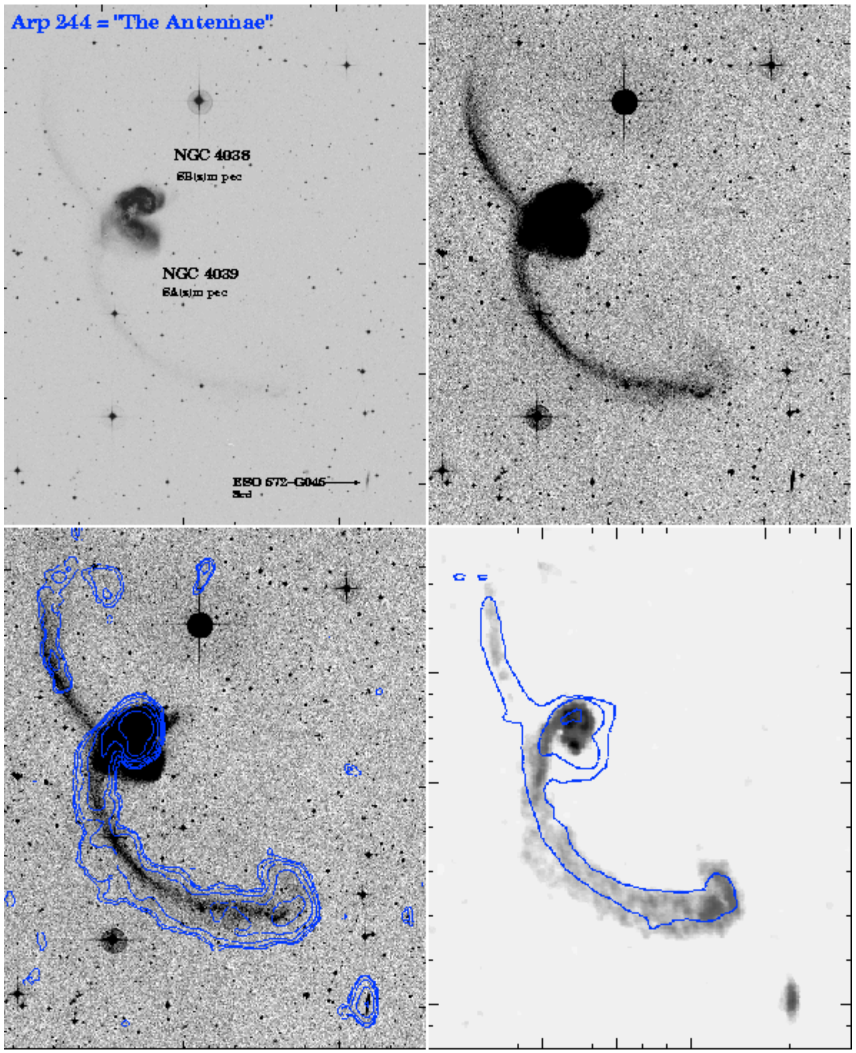
- The mass of the black hole is highly correlated with the luminosity and total mass of the spheroid component (spiral bulge or elliptical)

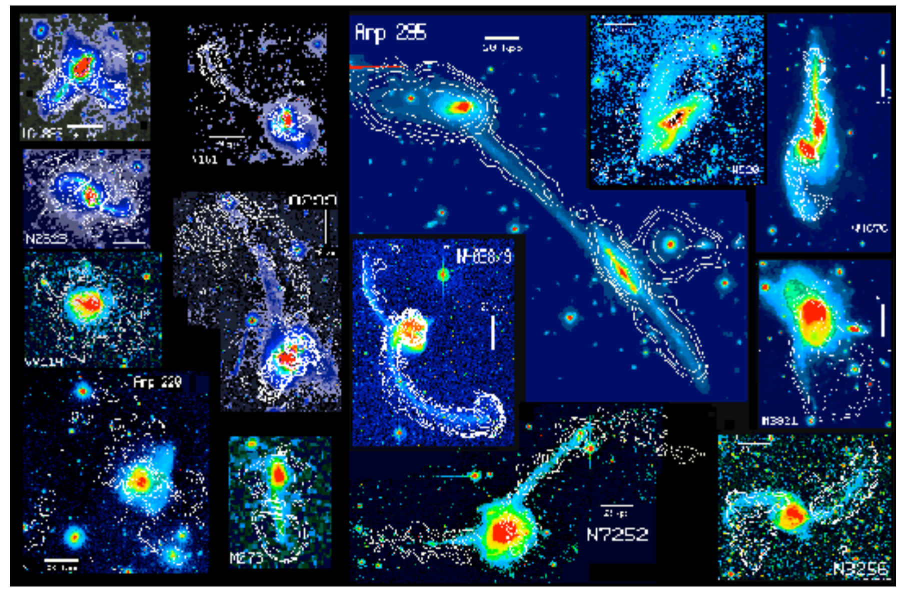


# Formation of Elliptical galaxies

- Mergers
  - Tails and bridges result of tidal forces
  - Two galaxies approach on parabolic orbits
    - Systems pass, turn around, but leave tails behind them
    - Ultimately the systems merge
- Simulated merger remnants follow $r^{1/4}$ law
- Observationally….
  - E+A galaxies look like merger remnants
  - Ellipticals reside in high density environments

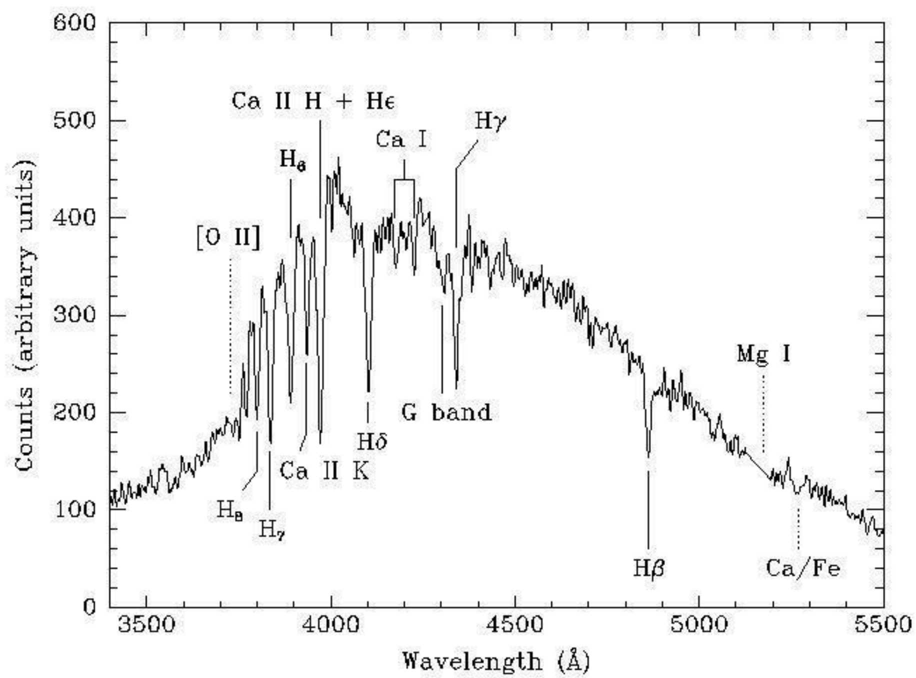
# Gallery of interactions




HI Rogues Gallery, J. Hibbard

# E+A galaxies




Zabludoff et al.

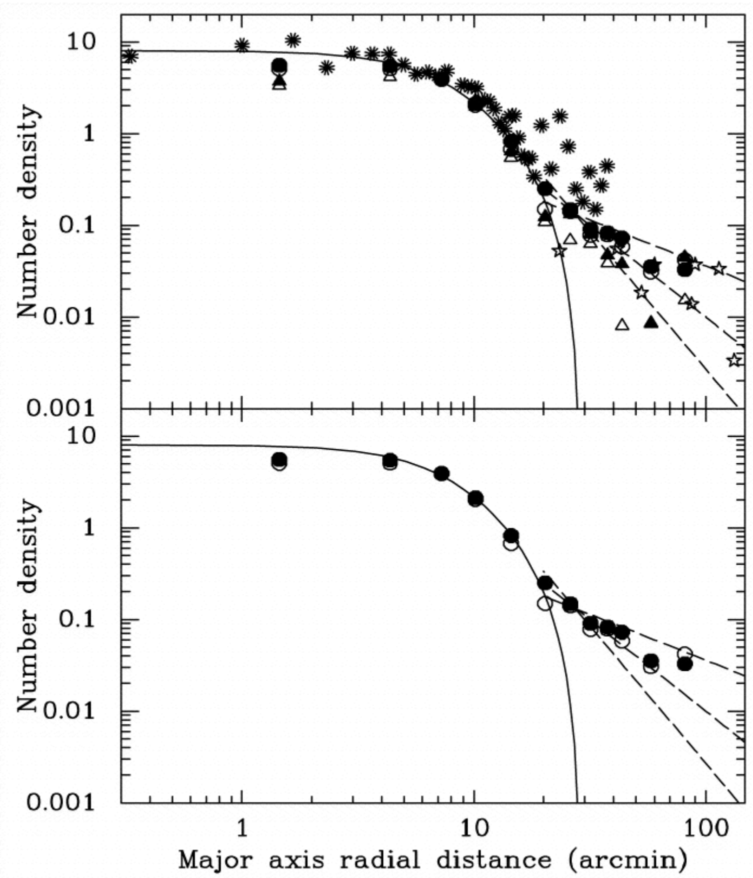
# Galactic Cannibalism

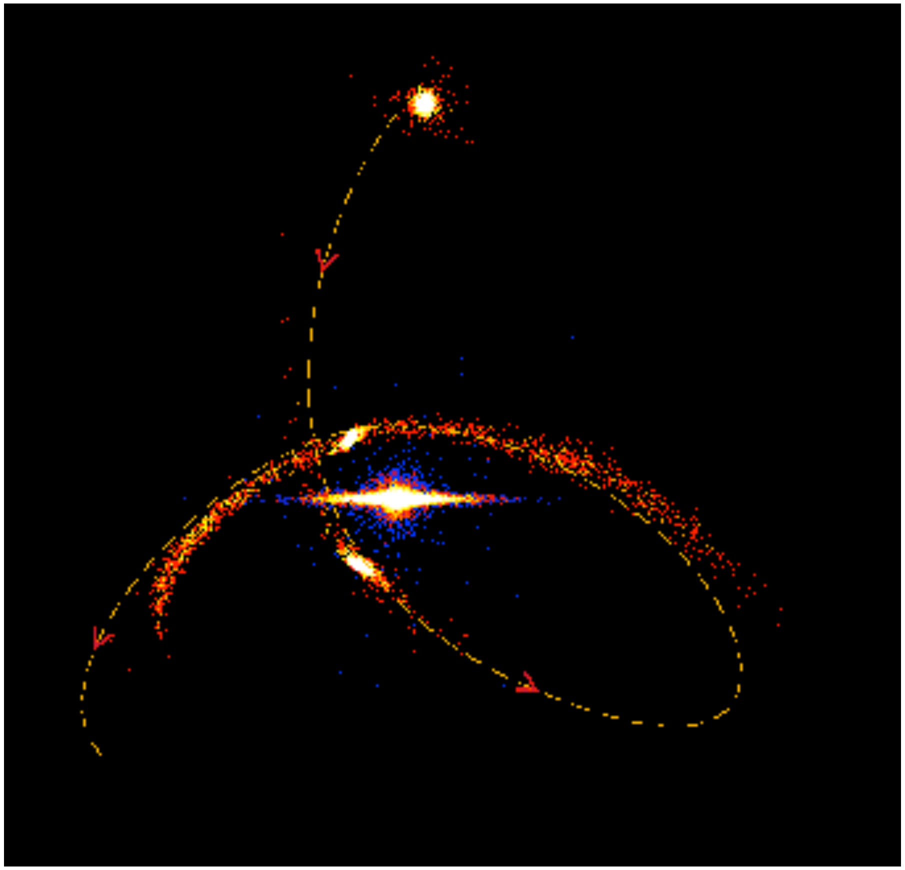
- "dynamical friction" induced cannibalism turns a normal elliptical into a cD giant ➔ some E's have multiple nuclei
- Dynamical friction = braking of some massive body via large numbers of weak gravitational interactions with a distribution of smaller masses (i.e. stars)
  - ➔satellite, M, deflects stars into building a trailing concentration of stars, increasing the gravitational drag, slowing down the satellite
- Applications:
  - Growth of elliptical galaxies
  - Milky Way is swallowing a number of its satellites
    - could the halo be comprised entirely of tidally stripped stars?

# Galactic Cannibalism (continued)

- Consider:
  - Satellite with mass, M
  - Stars with mass, m
  - Relative velocity, $v_0$
  - Impact parameter, b
  - Angle of deflection, $\theta$
- "reduced particle"; $\mu$ =mM/(m+M)
- Change in velocity parallel to the initial motion
  - $\Delta v = (2mv_0/M+m)[1+(b^2v_0^4/G^2(M+m)^2]^{-1}2\pi b\, db$
  - Then you integrate over impact parameter and some velocity distribution

# Growth of the MW Halo?



Majewski – real data

Johnston - simulation