Astronomy 730

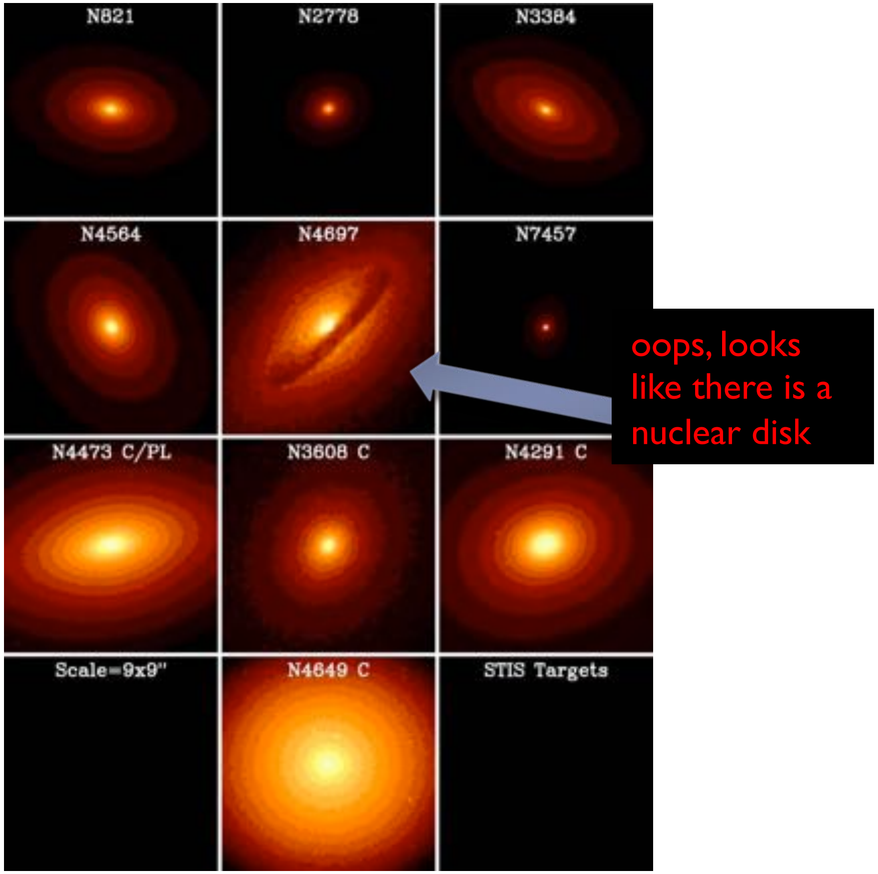
Elliptical Galaxies

Outline

- Elliptical galaxies
  - Basic properties
  - Stellar populations
- ISM: cool and hot gas
- Kinematics
  - Scaling relations
    - Faber-Jackson and Fundamental Plane
    - M_{BH} vs σ
  - Dark matter
- Topics in formation and evolution
  - E+A
  - Mergers

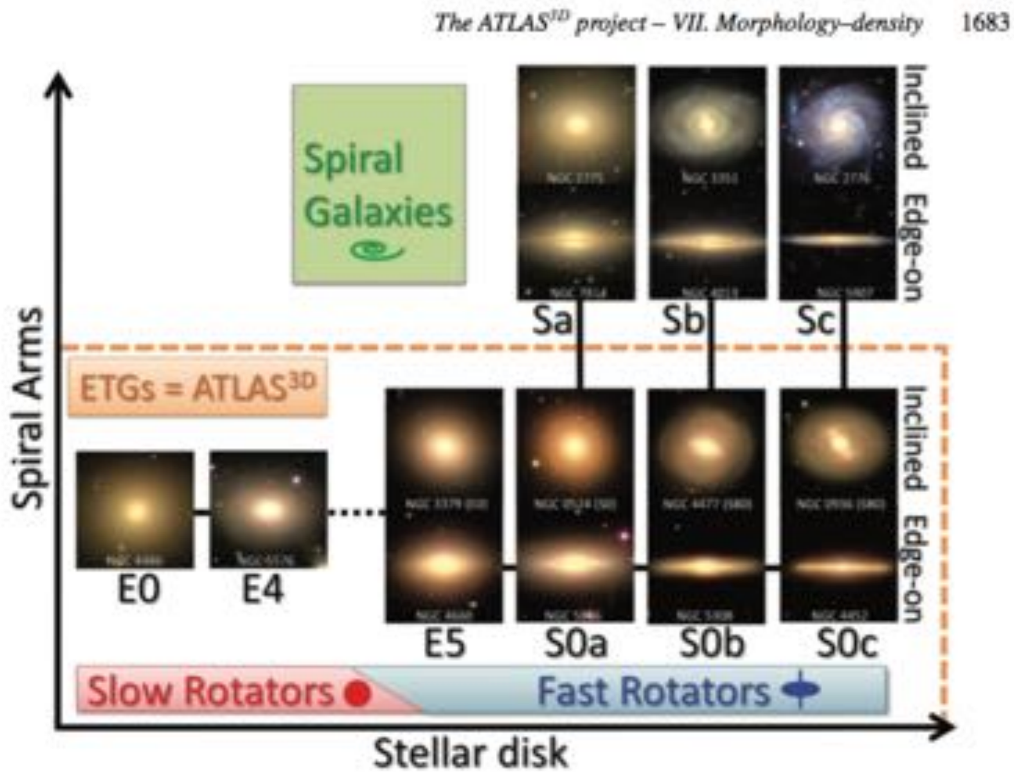
Elliptical Galaxies

Classic ground-based view in the optical

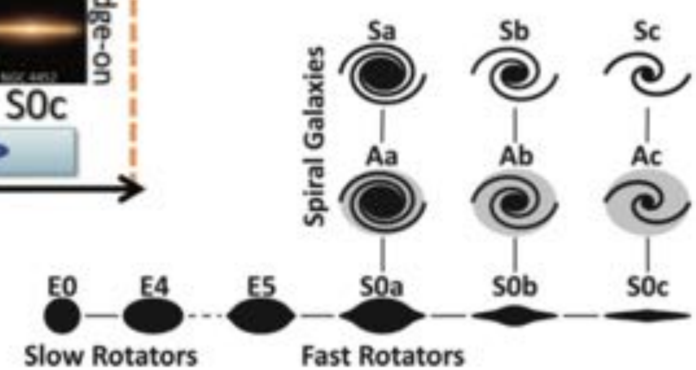


HST STIS images of cores

An Alternative to Hubble Tuning Fork



Cappellari et al. 2011
MNRAS, 416, 1680



Ellipticals: Basic properties

- Surface photometry
  - $I(r)=I_e \exp\{-7.67[(r/R_e)^{1/4}-1]\}$
  - "r1/4" law proposed by de Vaucouleurs
  - R_e= effective radius at which 1/2 of total light is emitted
  - Recall that this is a special case of the Sersic profile for n=4
  - Ellipticals show a range of n from 3 to 10.
  - Similar to bulges of early-type disk galaxies, but with higher index, n
- Classification: E0-E7 describing increase in flattening
- Stellar populations: old, metal rich
- Environment: dense, usually in clusters or rich groups
  - morphology-density relationship

Ellipticals: Basic properties *continued*

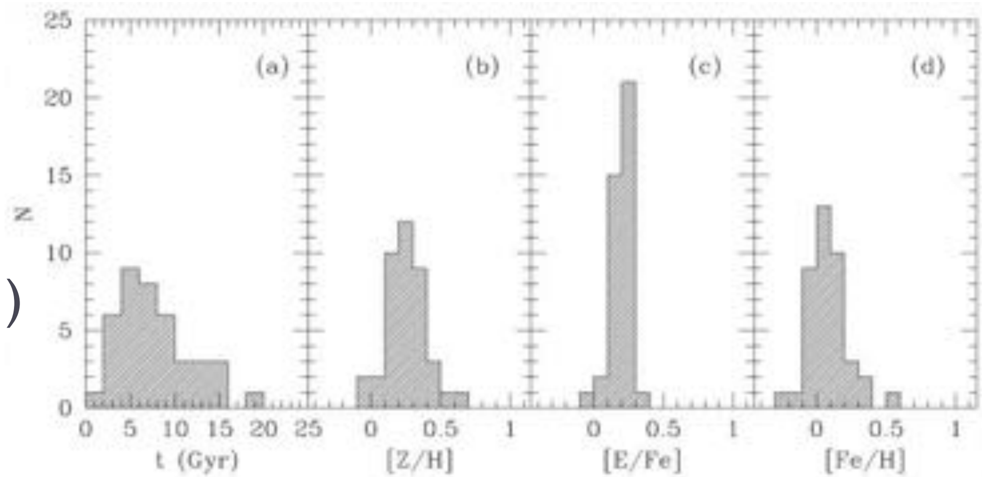
- Deviations from basic structure
  - Centers ➔in cD galaxies the surface brightness turns up in the center.
  - Halos ➔some have extended halos (excess light at large radii)
- What distinguishes ellipticals from spirals?
  - Ratio of V_c/σ
    - V_c is the circular velocity
    - σ is the velocity dispersion
    - In MWG V_c~220 km s-1, σ~50 km s-1; it's the opposite in ellipticals
  - Ellipticals are kinematically dominated by the velocity dispersion rather than the circular velocity.
    - Ellipticals are kinematically *hot*.
  - Presence/absence of large amounts of cool gas

Stellar populations

- Basic colors redder than spirals
  - Radial color gradient (redder in center)
  - Metallicity gradient: $d[Fe/H]/d\log_{10} r = -0.22$
    - Based on Mg, Fe lines
- Spectra (compare with a spiral)
  - Look like a combination of G, F, and K stars in the optical; prominent Mg and Fe lines
  - Need high resolution spectra over the 350-650 nm range + stellar absorption line models
- Age-abundance degeneracy
  - Can use H β line strengths (in absorption) as age indicator
    - Why does this work?

Stellar populations *continued*

- Trager et al. 2000
  - Age spread: 2-12 Gyr
  - Nearly solar metallicity ([Z/H])
  - Slightly subsolar [Fe/H]
  - Yields a high [Mg/Fe] ratio



- Other fits: old population with "frosting" of younger stars
- Bottom line: good fraction of old stars, but how old and real fraction is not well known.

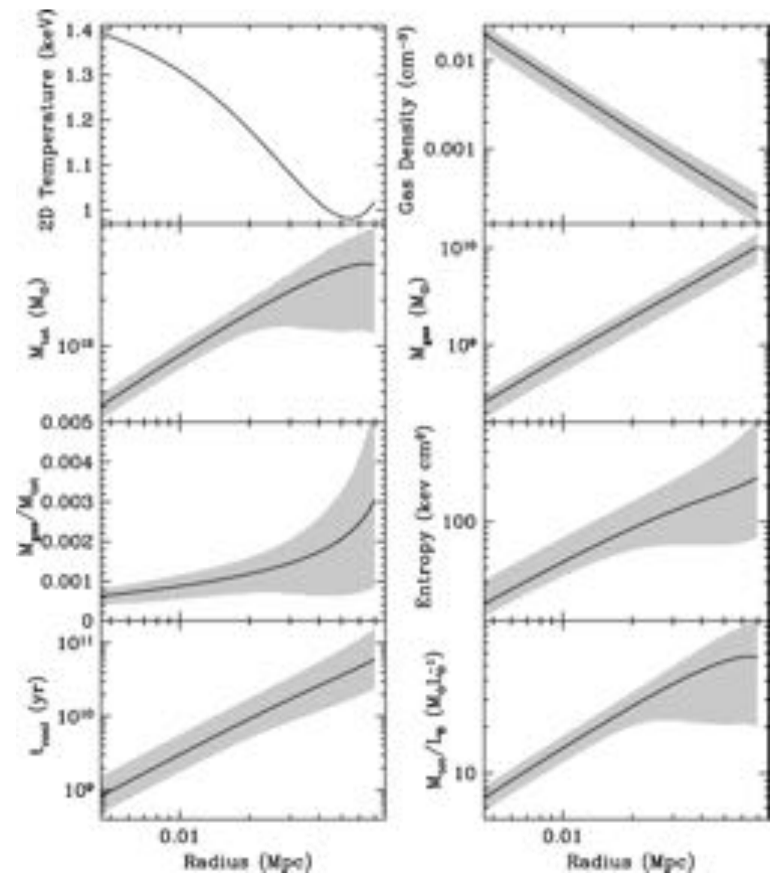
ISM in Ellipticals

- Cool gas
  - Usually outside of main galaxy
  - Associated with shells
  - Disks out to large radii
  - (exception: dwarf ellipticals with nuclear clouds)
  - No correlation between presence of cool gas and any other property of the galaxy
- Ionized gas – not much outside of nuclear regions (i.e., little star formation)
- Hot (x-ray) gas – *lots!*

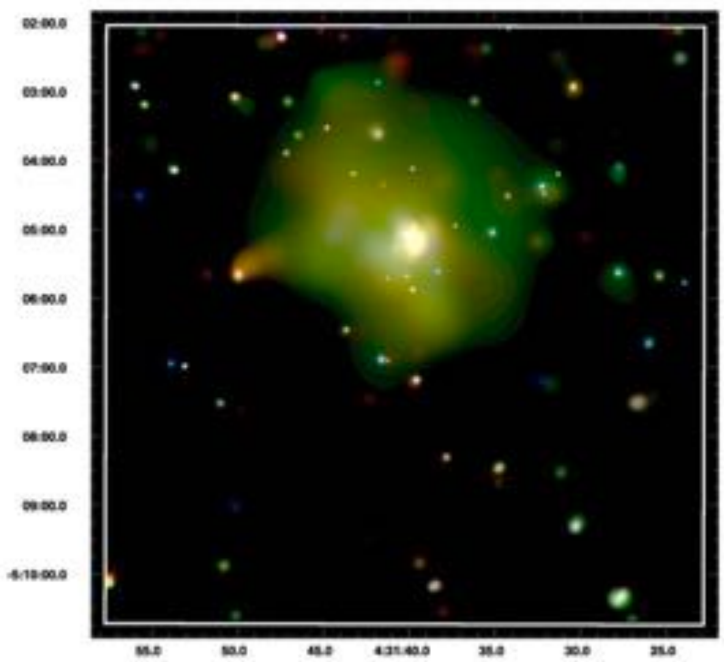
Hot Gas in Ellipticals

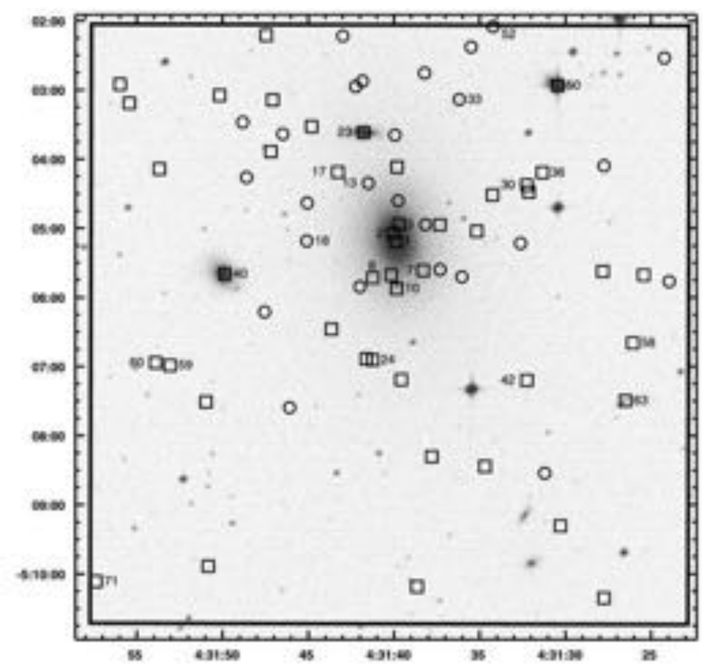
- L_X goes as $L_B^{1.6\text{-}2.3}$ (empirical relation)
- ρ goes as $r^{-3/2}$
- $M_{gas} \sim 10^9$–$10^{11} M_\odot$
- Origin of hot gas
  - Reservoir
  - External
  - Internal:
    - Mass return from AGB stars $\sim 1.5 \times 10^{11} M_\odot yr^{-1} L_\odot^{-1}$
    - Heated by Sne (what kind?), thermal motion of stars at 200-300 km s^{-1}

Radial distribution



X-ray to Optical comparison





Stellar Kinematics

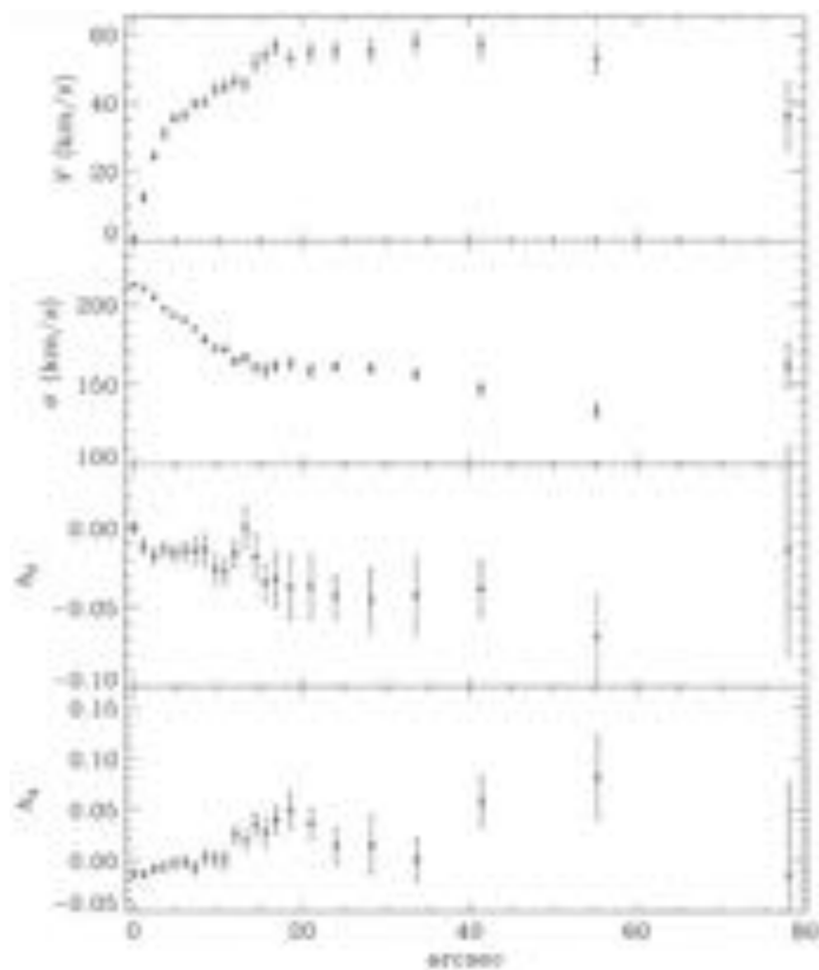
- Measuring intrinsic shape/potential:
  - 1. Surface photometry → mass distribution → potential (Φ, M(r) model) → orbit library → superposition of orbits → iterate
  - 2. Surface photometry + resolved velocity fields and velocity dispersion maps
- You measure of line-of-sight velocity distribution → $<v_{los}> = \int F(v_{los}) v_{los} dv_{los}$
- Then, $\sigma^2 = \int (<v_{los}> - v_{los})^2 F(v_{los})\, dv_{los}$
- This accounts for the streaming and random motion of stars.

Stellar Kinematics *continued*

- LOSVD
  - Assume a Gaussian velocity distribution function (F) to this makes things easier.
  - F ➔ $\exp[-(<v_{los}>-v_{los})^2/2\sigma_{los}^2]$ ➔ e^{-b}
    - $b = (1/2)w^2$, $w = (<v_{los}>-v_{los})/\sigma_{los}$
  - This all yields a symmetric line profile.
    - Remember we're sampling a specific absorption feature (e.g. a Mg II line)
- But reality isn't all that symmetric, so we need some way to describe deviations from Gaussian ➔
  - "Gauss-Hermite" series which combines a Gaussian with an orthogonal set of polynomials
  - F goes as: $e^{-k}[1 + \Sigma_{k=3,n} h_k H_k(w)]$
    - this is a polynomial of order k, with some coefficient h

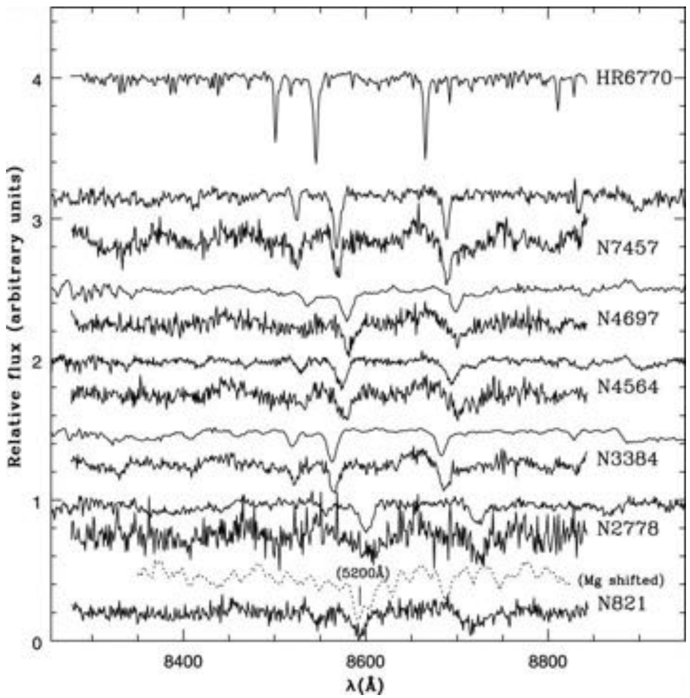
Gauss-Hermite information

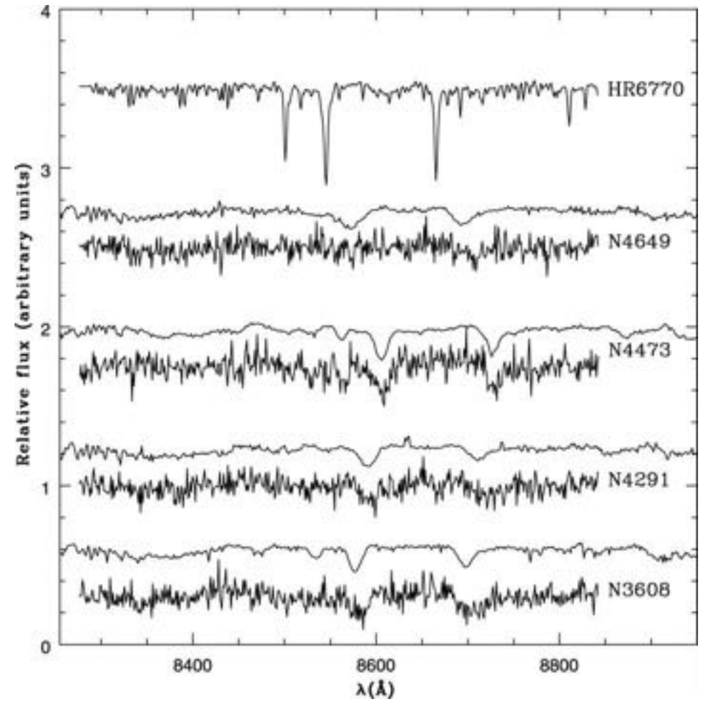
- Describe stellar kinematics with four terms:
  - v, σ^2, h_3, h_4
- Third term:
  - $h_3\,(2w^3-3w)/(3^{1/2})$
  - h_3 ➔ measures "skewness" or deviation from symmetry. Large positive h_3 represents a secondary bump at v > v so that the peak of the line is now < v
- Fourth term:
  - $h_4\,(4w^4-12w^2+1)/(24^{1/2})$
  - h_4 ➔ measures "kurtosis" or symmetric departures from a Gaussian. Large h_4 yields a boxy profile centered on v



The data…

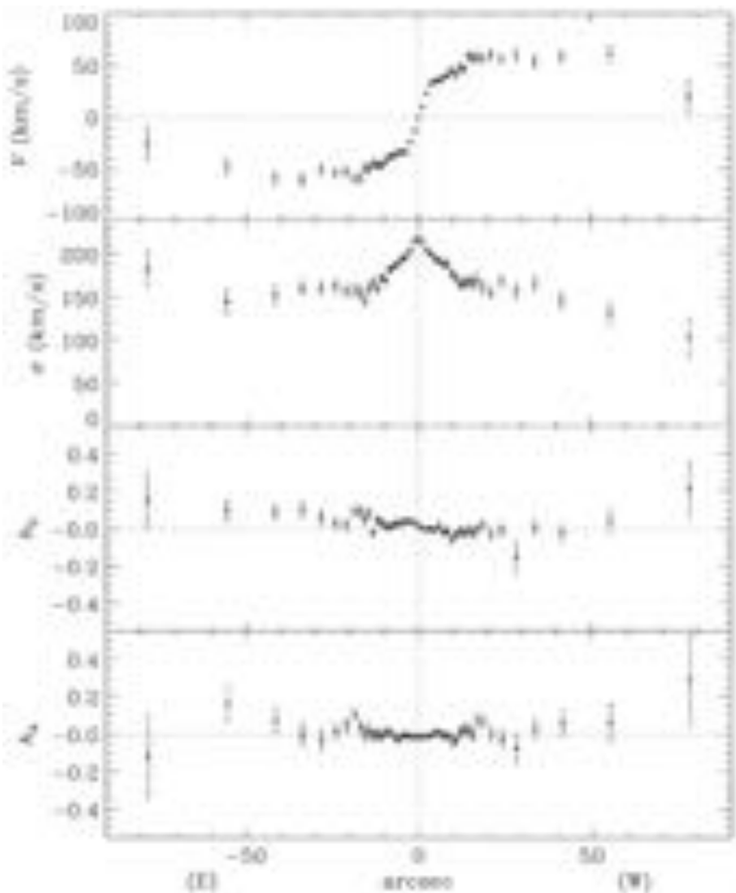
- Call near-infrared triplet
  - 3 strong lines prominent in cool stars

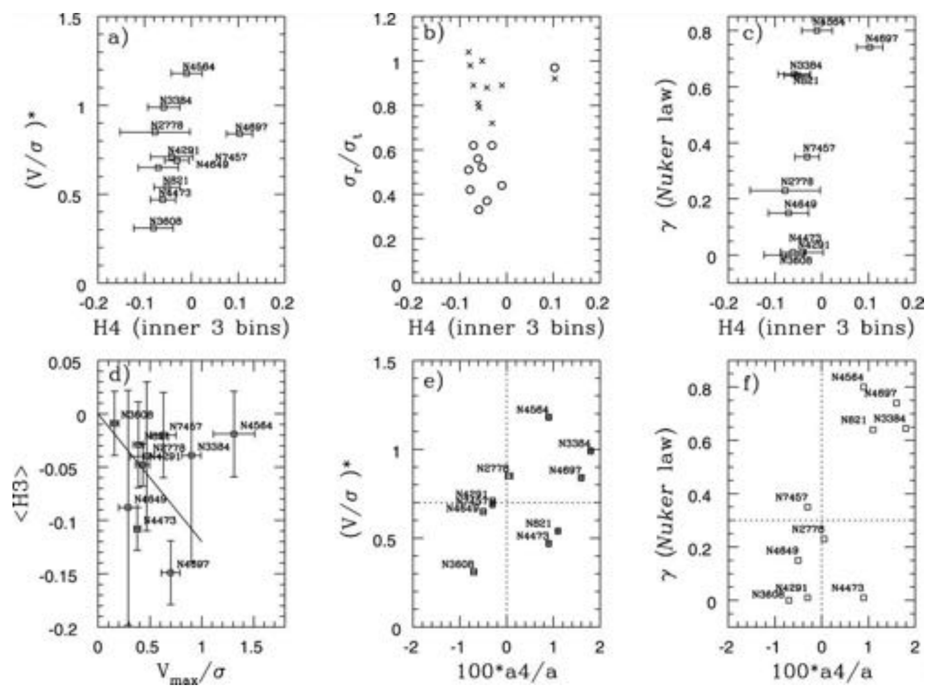




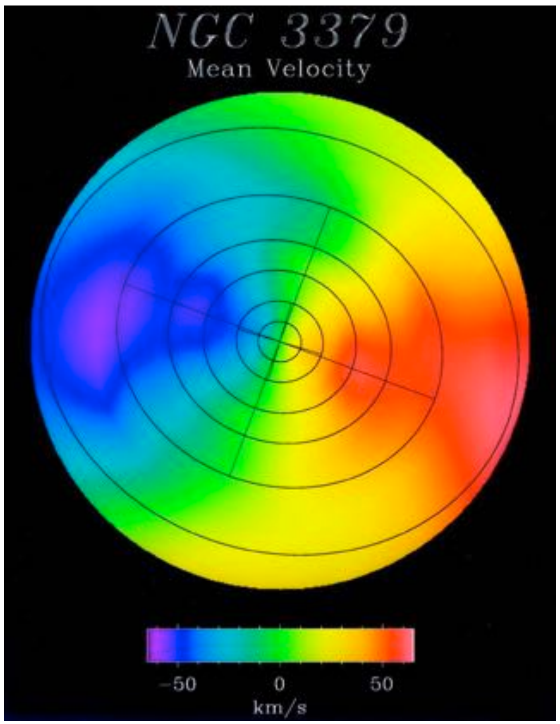
  - Traditionally, primary lines (absorption) have been in the blue-visible, including Hbeta, MgI, and Fe I

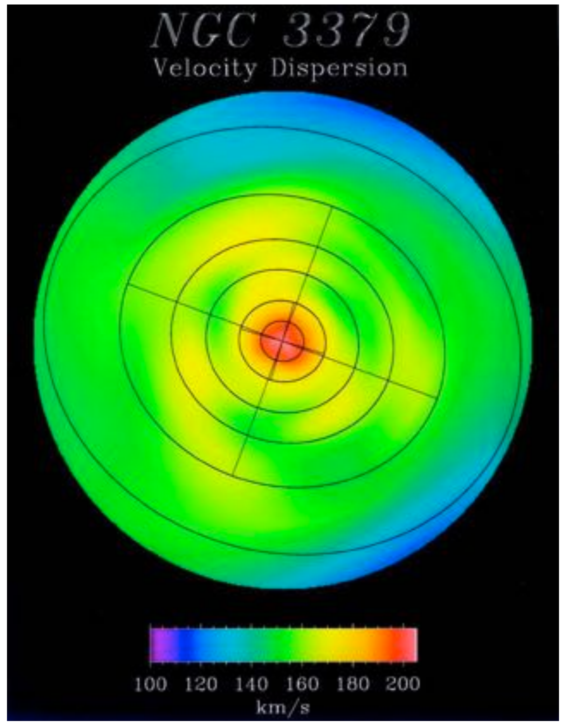
Kinematic and structural parameters

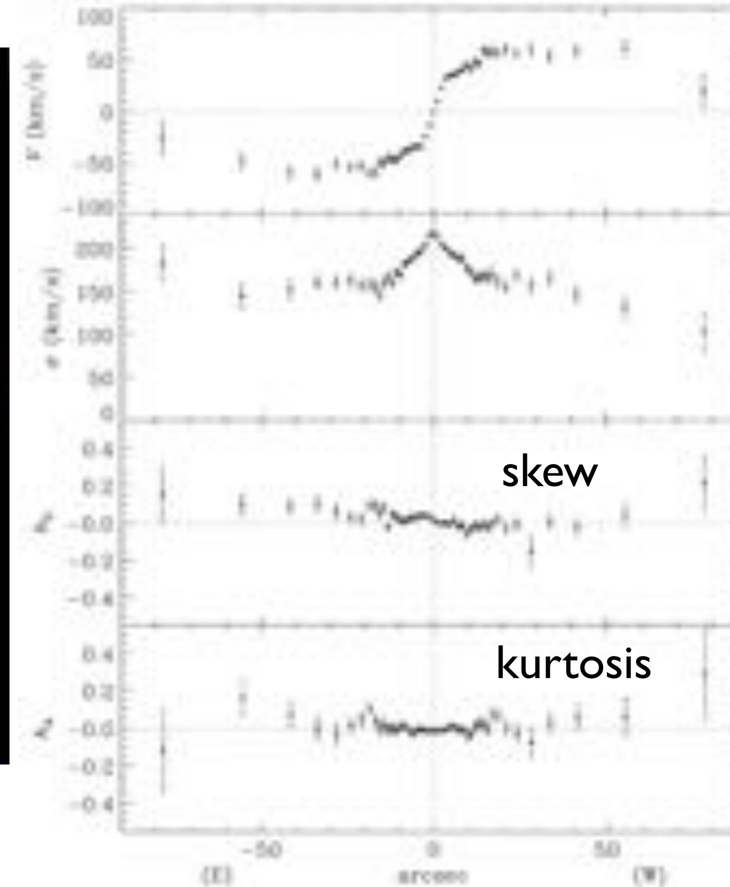




Elliptical galaxies do rotate …







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

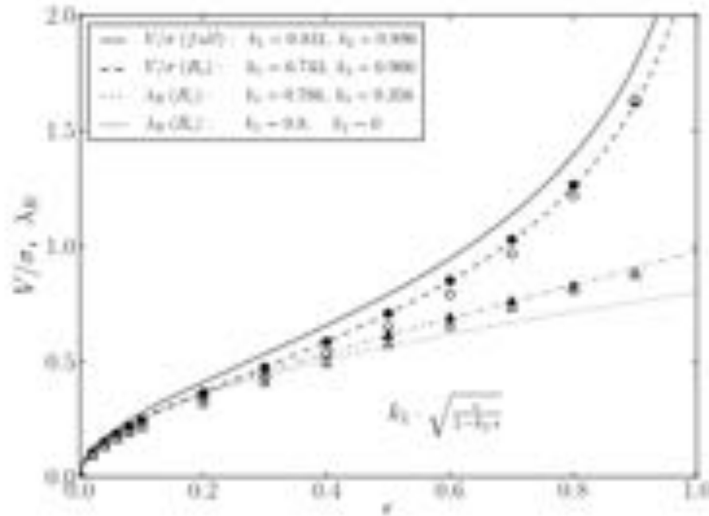
Galaxy spins: angular momentum

- Emsellem et al. 2007, MNRAS, 379, 401
- Emsellem et al. 2011, MNRAS, 414, 888

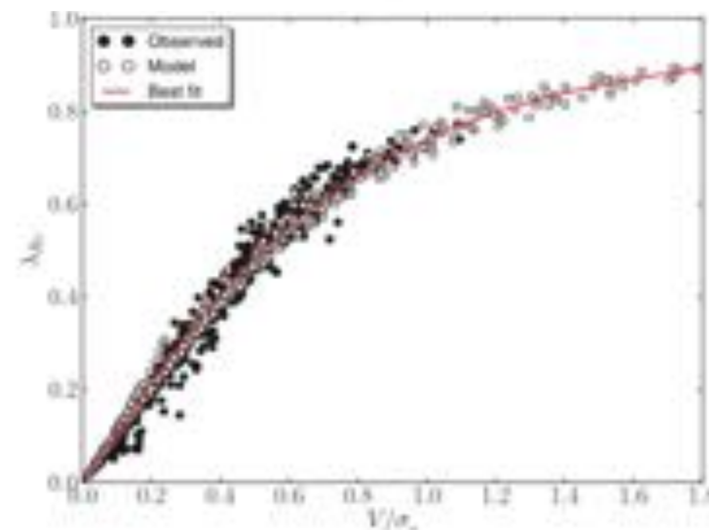
$$\lambda_R \equiv \frac{\langle R\,|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle},$$

which transforms into

$$\lambda_R = \frac{\sum_{i=1}^{N_p} F_i R_i\,|V_i|}{\sum_{i=1}^{N_p} F_i R_i \sqrt{V_i^2+\sigma_i^2}},$$

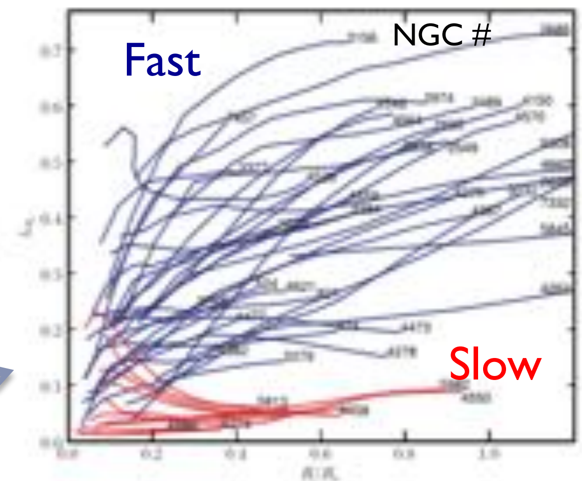


Compare λ to V/σ:

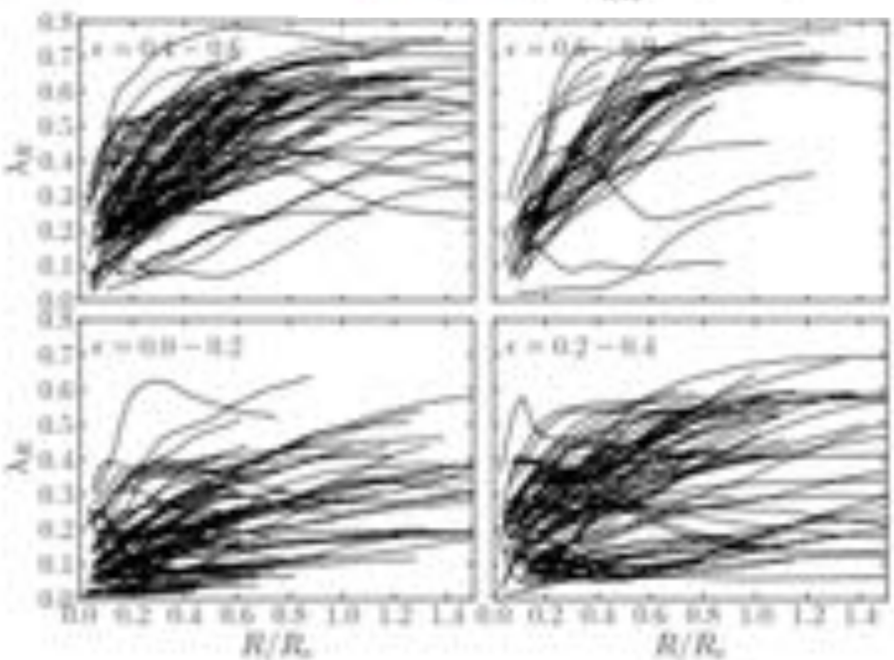


Angular momentum (continued)

- Need to pick a fiducial radius, say, based on the light distribution.
- R_e or some scale of it is reasonable if light traces mass
- We've already seen this is useful as a classifier (e.g., Cappellari+2011)



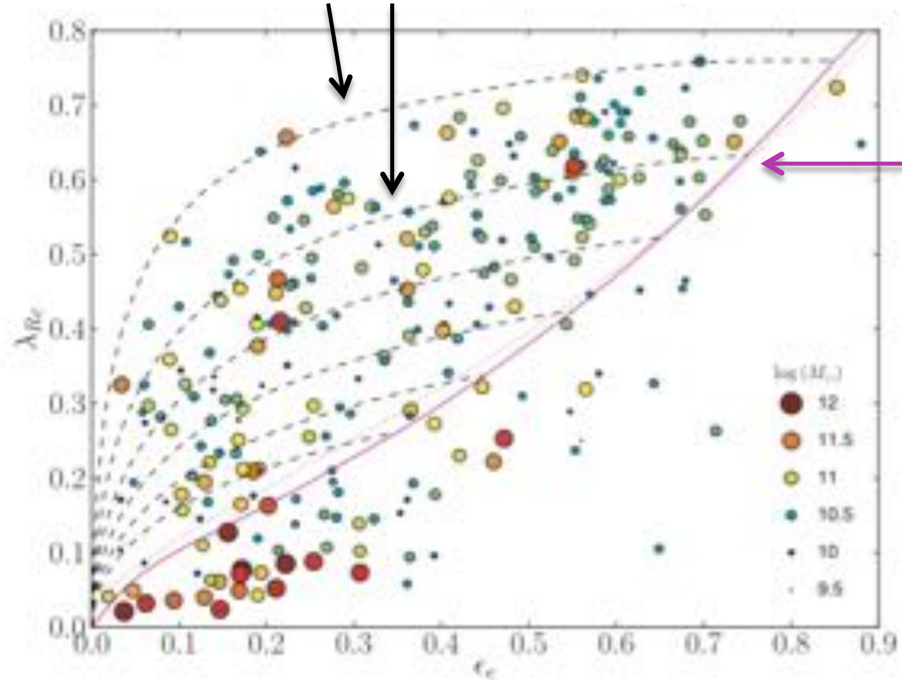
- Emsellem+2007, SAURON survey: E/S0
- Emsellem+2011, ATLAS^{3D}: ETGs (includes E/S0)



Angular momentum (continued)

ATLAS[3D] results at $R = R_e$

ε_{intr} = 0.85, 0.75, 0.65, 0.55, 0.45 and 0.35



$\beta = 0.70 \times \varepsilon$
Integrated to infinity

$\beta = 0.65 \times \varepsilon$
Integrated to 1Re

$\beta = 1 - \sigma_z^2/\sigma_R^2$

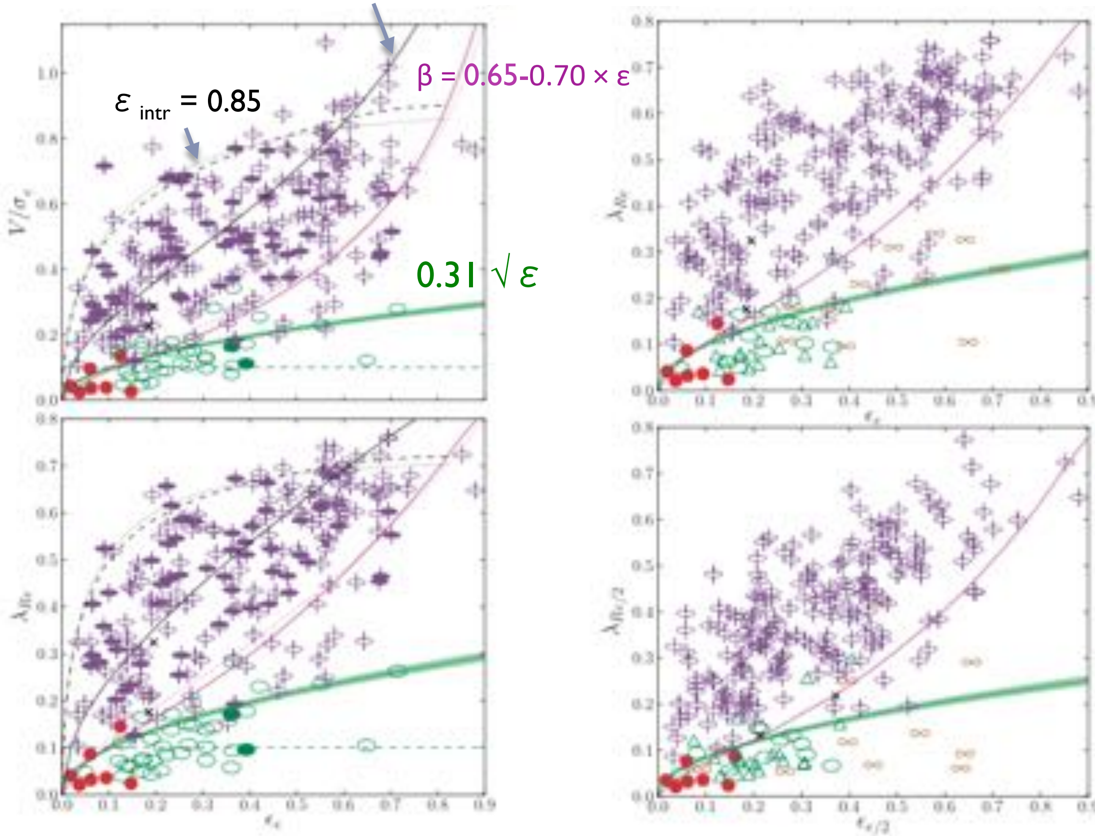
Emsellem+11; see also Cappellari+2007, MNRAS, 379, 418

Angular momentum (continued)

ATLAS[3D] results: λ cleaner separator than V/σ, R_e better than $R_e/2$, but latter useful for isolating special cases (KDCs, 2σ)

isotropic oblate systems viewed edge-on.

Filled: bars



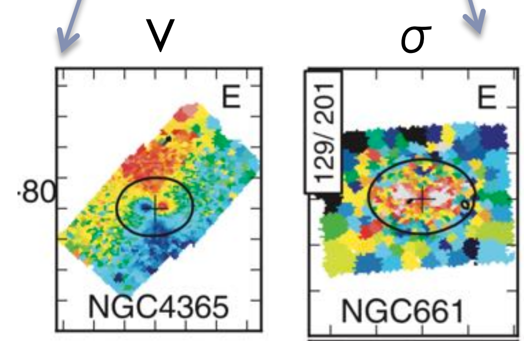
Purple: regular rotatotrs

Green: non-regular rotators

Red: non-rotators

Triangles: KDC

Leminscates: 2σ



Results

- Pick a potential that will fit observed kinematics and surface brightness profile, e.g.,
  - $\Phi(R,Z)=(1/2)v_0^2\ln(R_c^2+R^2)$
  - Use four key kinematic parameters to characterize orbits and hence shape of potential (recall SOS program in HW3)
- Use tracers at large radii (PN and GCs) to obtain over-all velocity
- Findings:
  - M/L ratio increases with R
  - $M/r = 5 \times 10^{12} M_\odot \mathrm{kpc}^{-1}$
  - M/L ~ 100-200 in some cases
  - Kinematics dominated by a dark halo beyond 1-2 R_e
  - "flat" σ vs R curves (just like spirals)
  - (further confirmation of dark halo comes from power law like distribution of hot x-ray emitting gas)

True shape of elliptical galaxies

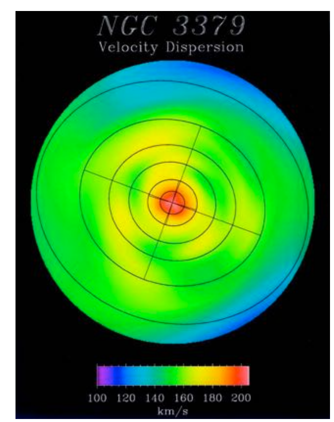
- We see the 2-dimensional projection of a three dimensional thing: How can we tell the true shape?
  - Prolate or oblate?
    - Orbits
    - Viewing angle
    - Velocity fields
- Look for deviations in the 2-dimensional data ➔ twists in the isophotes
  - Peng, Ford, Freeman (2004) use planetary nebula 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, σ, μ_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
σ: the velocity dispersion
μ_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 σ measured?
Recall:



Fundamental Plane (2-D projections)

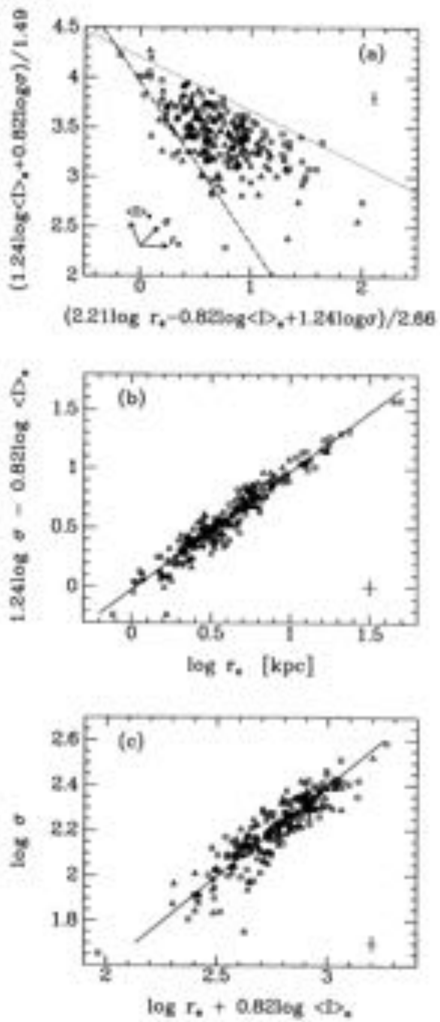
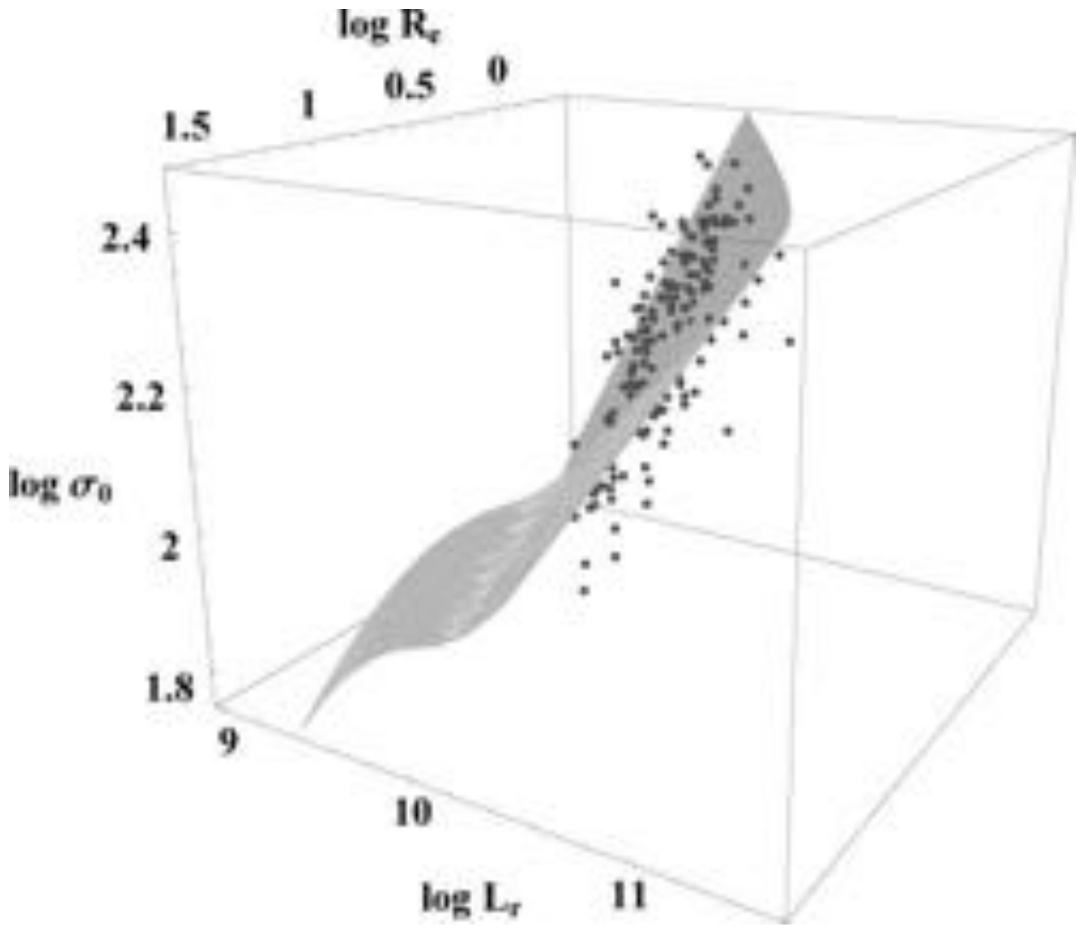


Figure 1. (a) The FP in Gunn r as derived in equation (1) shown face-on for all galaxies in the sample. The arrows in the lower left corner of the panel show in which directions the measured parameters increase. The dashed line shows the selection effect due to a limiting magnitude of −20.45 mag in Gunn r. This is the magnitude limit for the Coma cluster sample. The upper boundary (dotted line, $y = -0.54x + 4.2$) 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.

$$\log r_e = \underset{\pm 0.05}{1.35} \log \sigma - \underset{\pm 0.03}{0.82} \log \langle I \rangle_e + \gamma_r$$

Fundamental Plane (3-D)

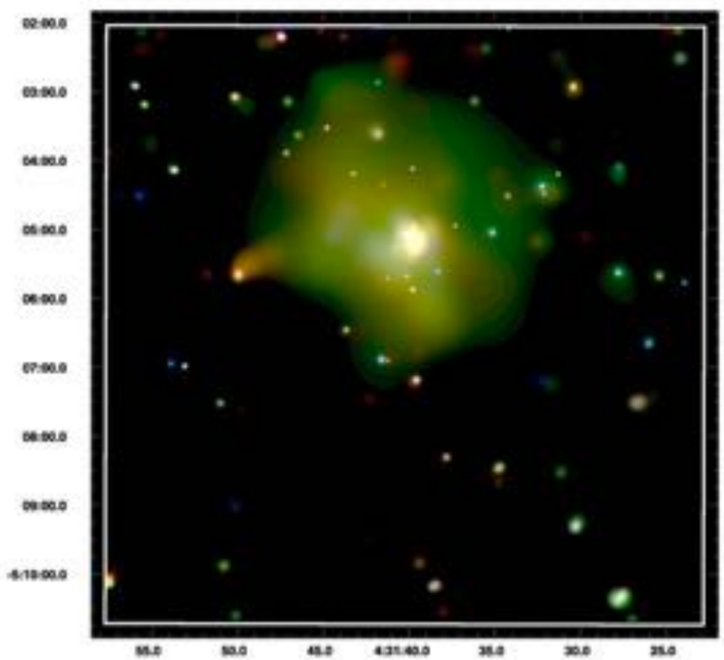


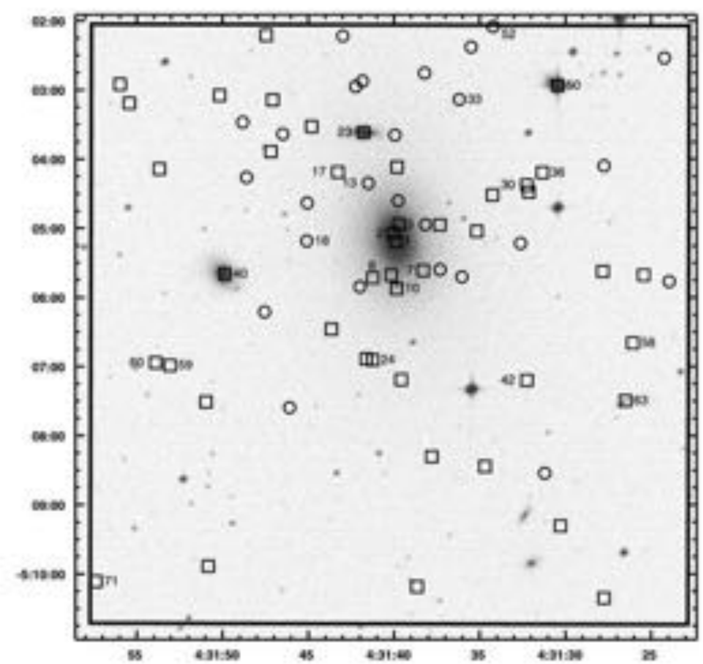
Hot Gas and Dark Matter

- 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

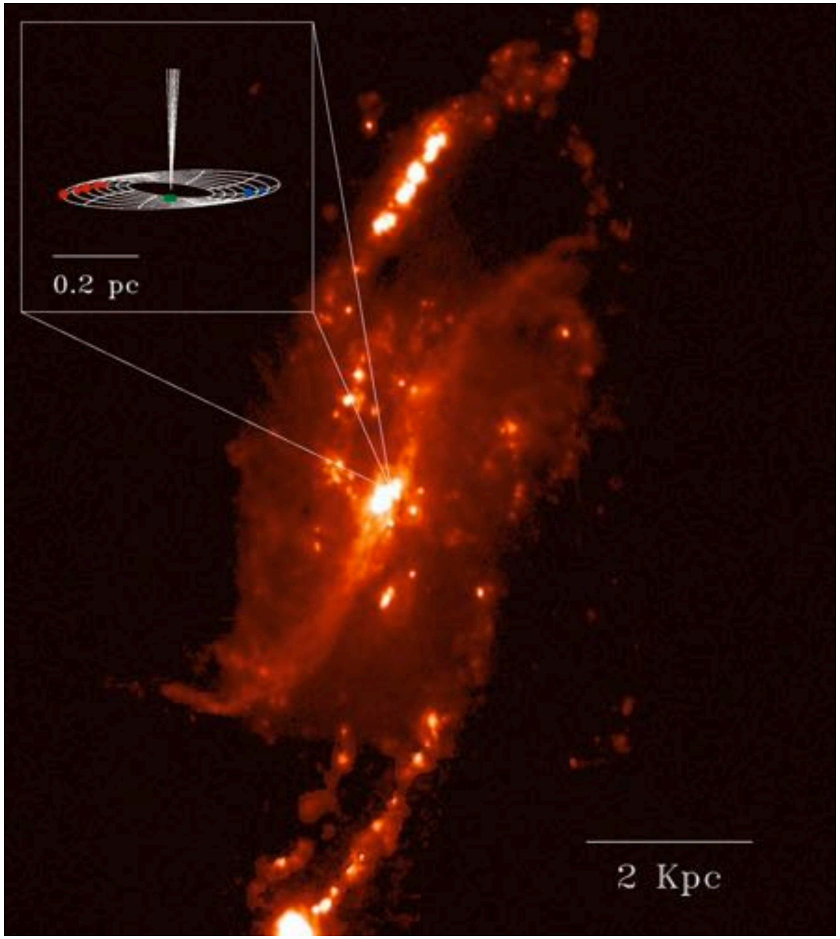
- Apply something like the CBE
- Jeans equation for spherical, isotropic stellar system
  - $d(\rho\ \sigma^2)/dr = -GM(r)\,\rho\,/r^2 + \ \rho\, V^2/r$
  - Adopt a mass model
    - e.g. isothermal sphere, NFW halo
      - This is only for the dark matter
    - e.g. Hernquist: $\rho\,(r)=(M_l a/2\pi)(1/r(r+a)^2)$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

Central regions

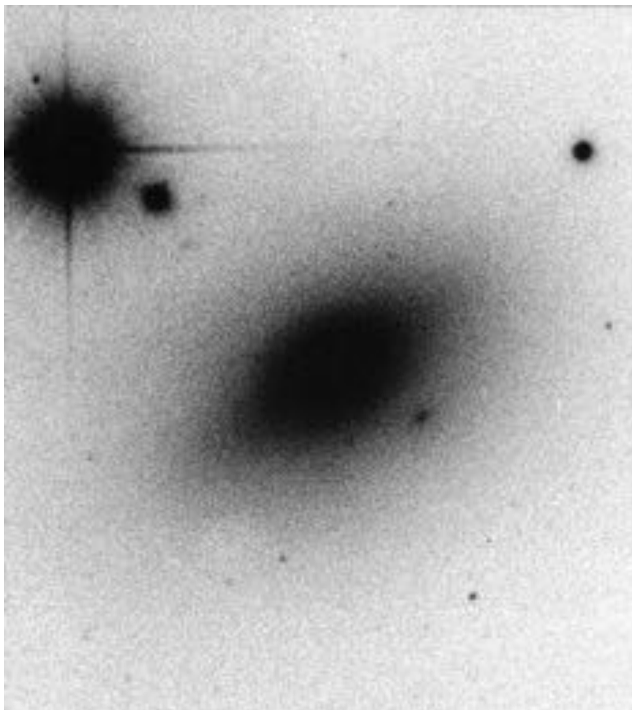
- Based on high-resolution photometry
  - try to fit some function to the observed light distribution
  - looking for deviations from Sersic profile
    - $I(r)=I_b 2^{(\beta-\gamma)/\alpha}(r_b/r)^{\gamma}[1+(r/r_b)^{\alpha}]^{(\gamma-\beta)/\alpha}$
      - r_b = "break" radius
      - γ = inner logarithmic slope ($r < r_b$) ➔ $\gamma = -d \log I / d \log r$
      - β = outer slope
      - α = 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

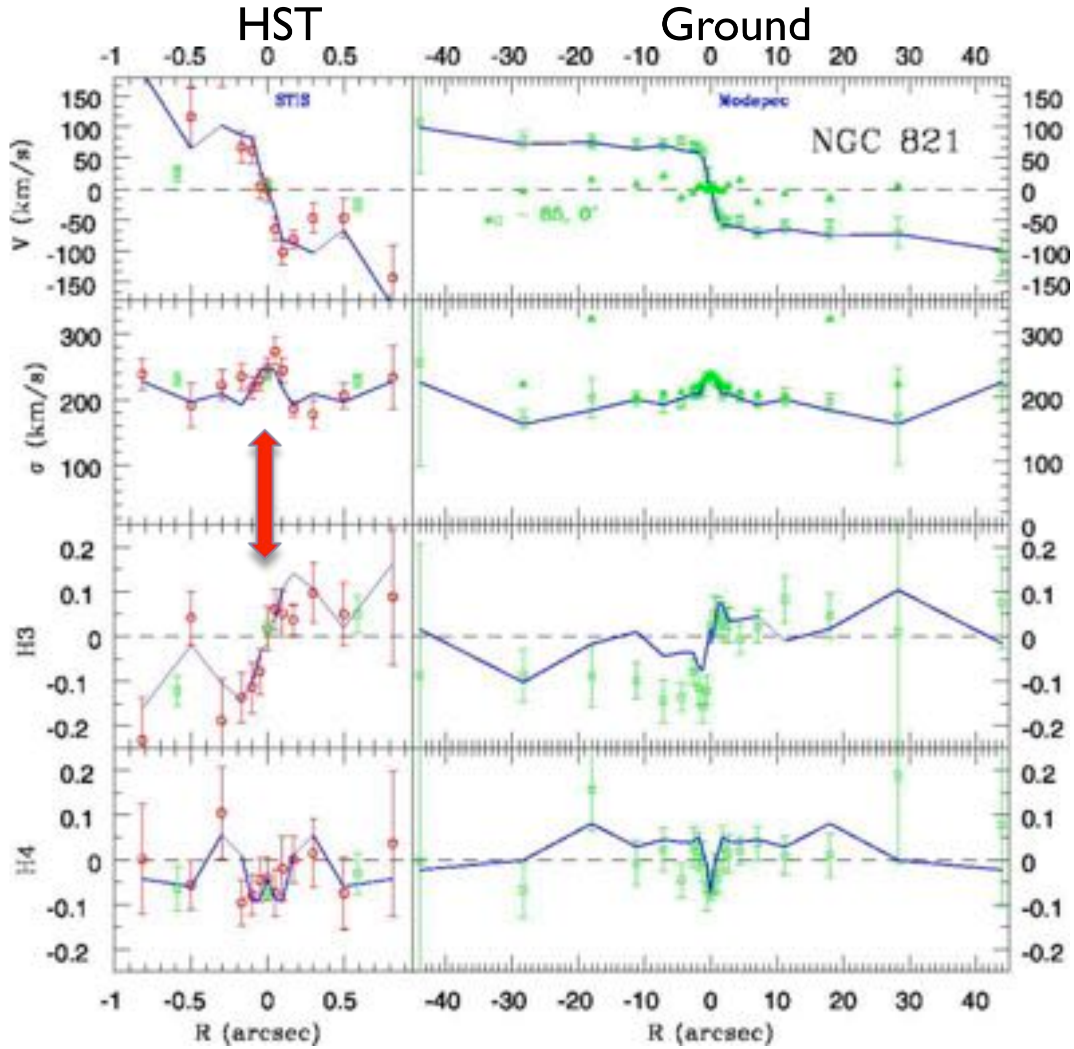
- How do you tell?
- Ellipticals
  - Central surface brightness
  - Velocity dispersions
  - M_{BH}/σ relationship
- Spirals
  - Rotational velocities
  - VLBA measurement of masers in NGC 4258



Case study: NGC 821

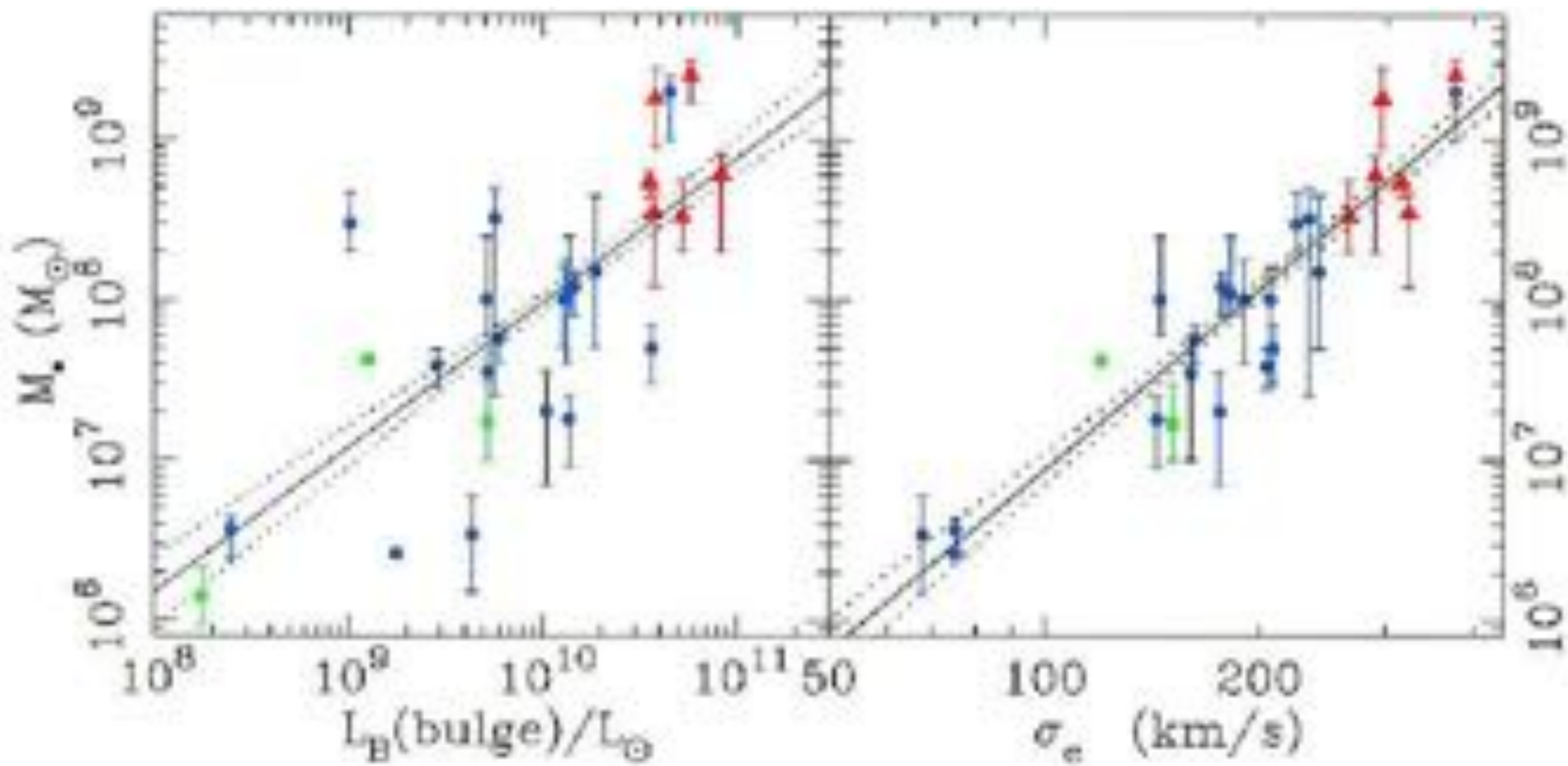


Ground-based image



M_{BH}/σ relationship

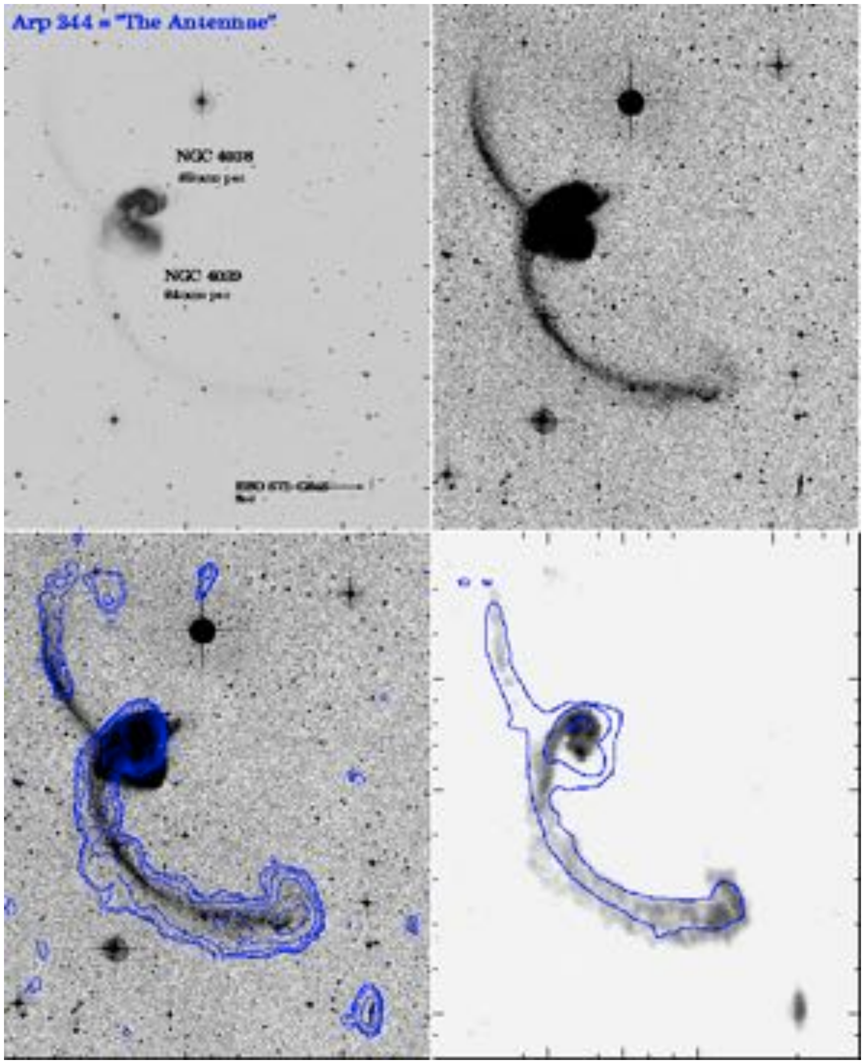
- The mass of the black hole is highly correlated with the luminosity and total mass of the spheroid component (spiral bulge or elliptical)

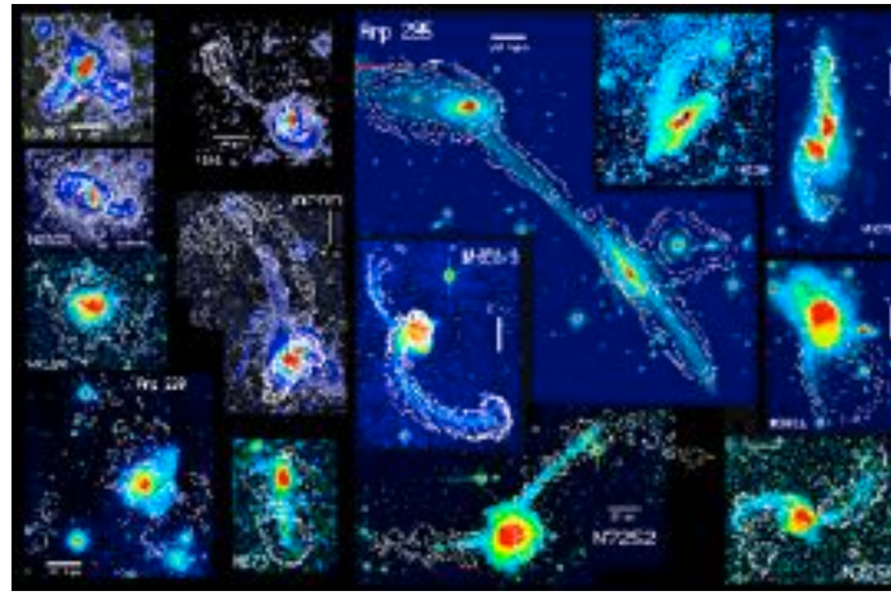


Formation of Elliptical galaxies

- 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

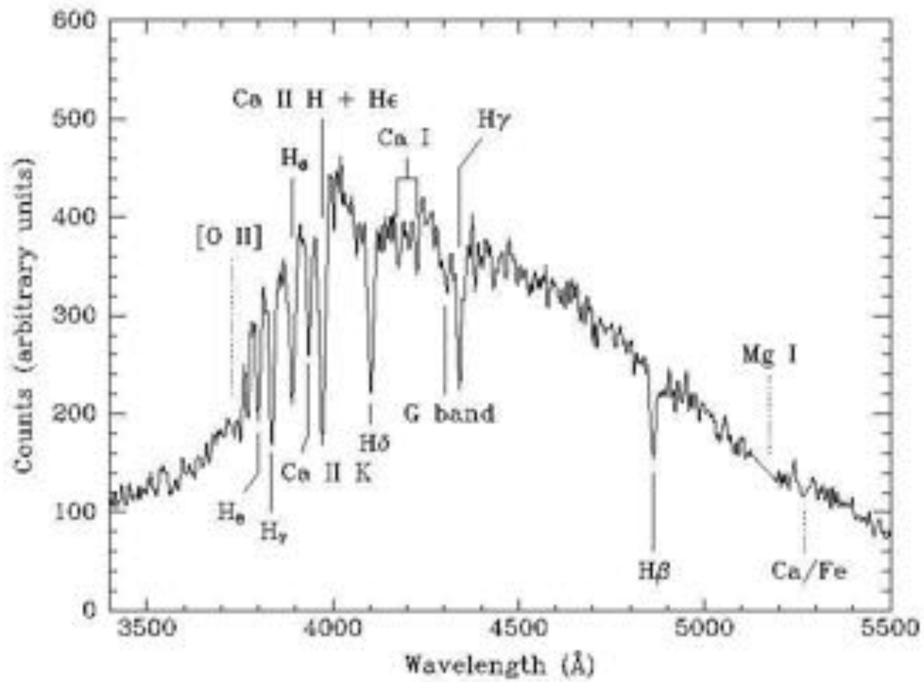
Gallery of interactions





HI Rogues Gallery, J. Hibbard

E+A galaxies



Zabludoff et al.

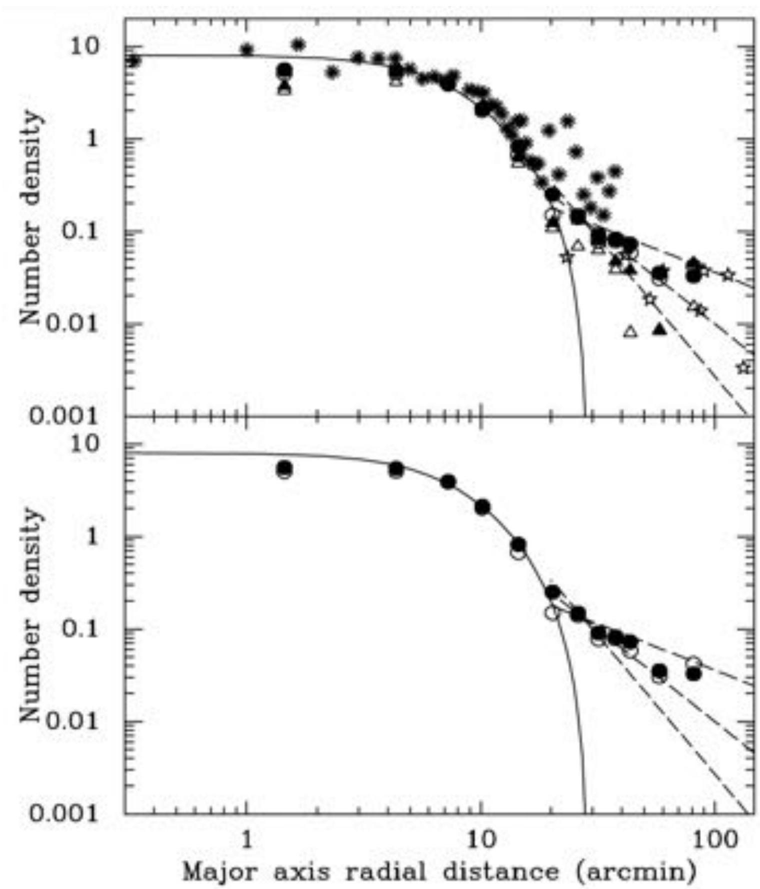
Galactic Cannibalism

- "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?

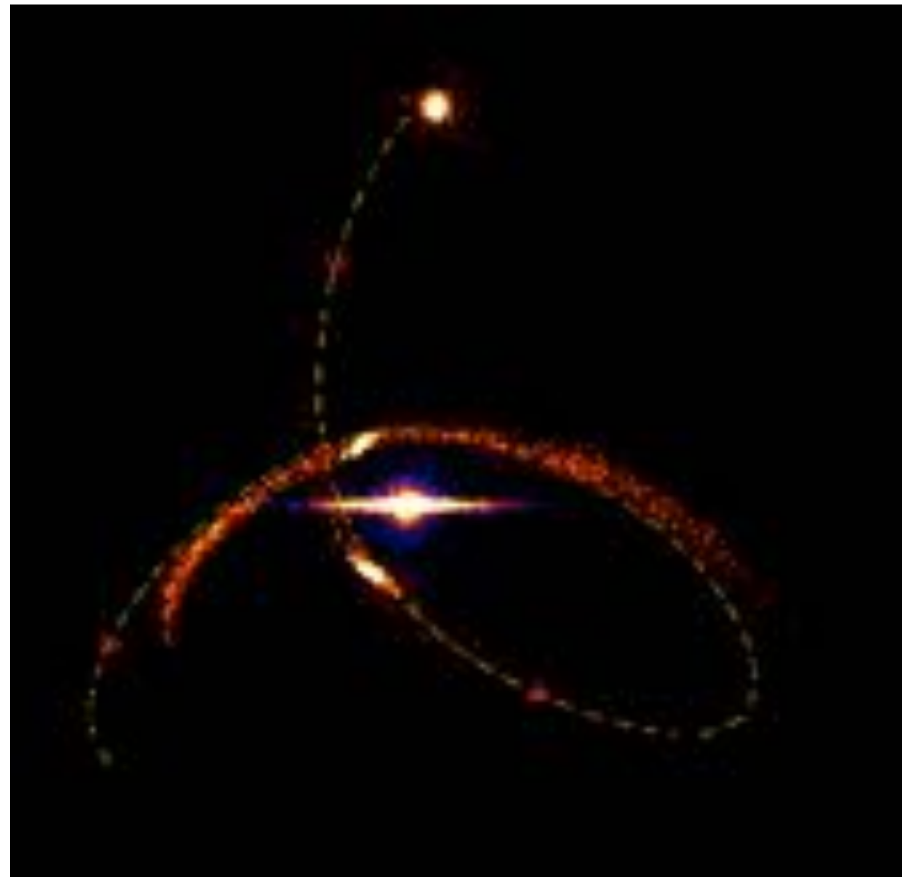
Galactic Cannibalism (continued)

- Consider:
  - Satellite with mass, M
  - Stars with mass, m
  - Relative velocity, v_0
  - Impact parameter, b
  - Angle of deflection, θ
- "reduced particle"; μ =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?



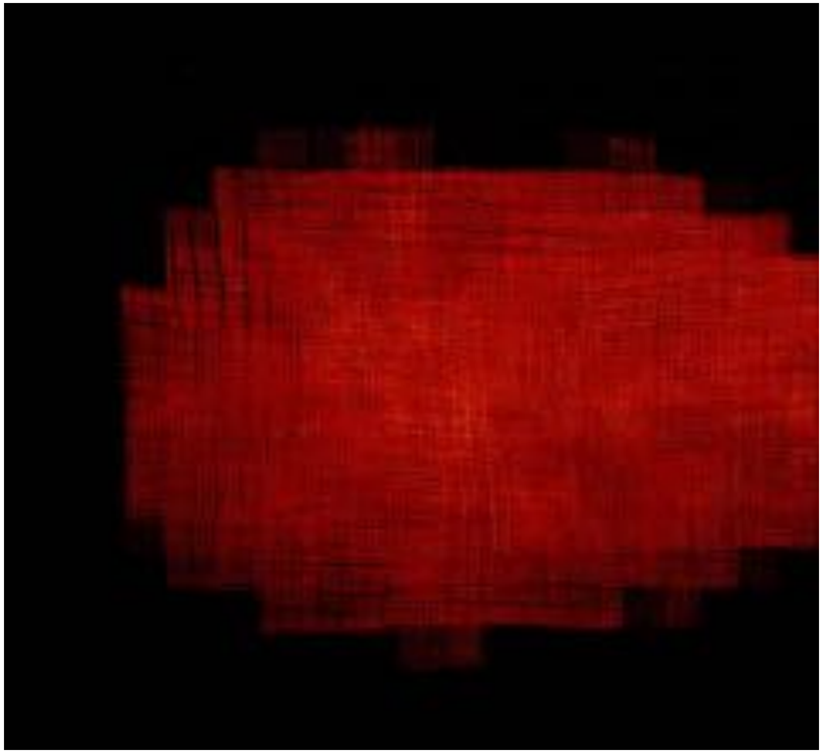
Majewski – real data



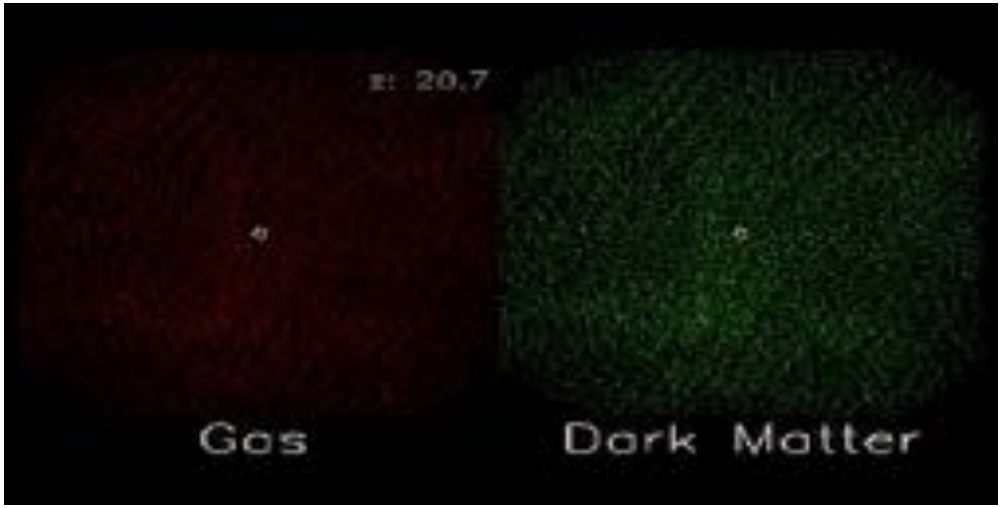
Johnston - simulation

Making galaxies

elliptical



spiral

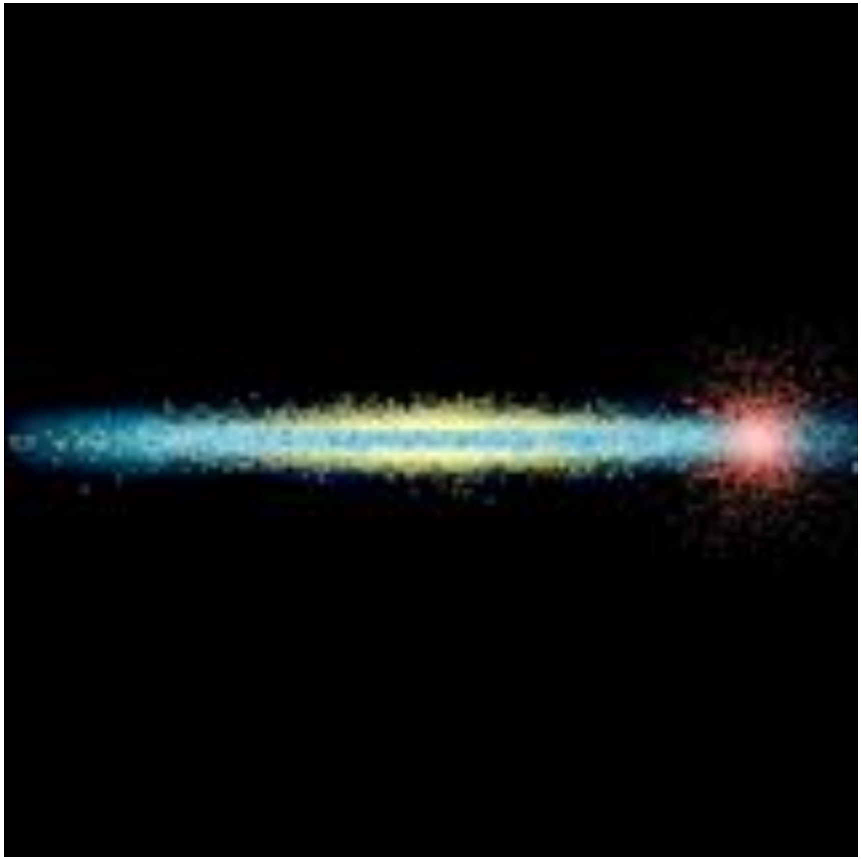


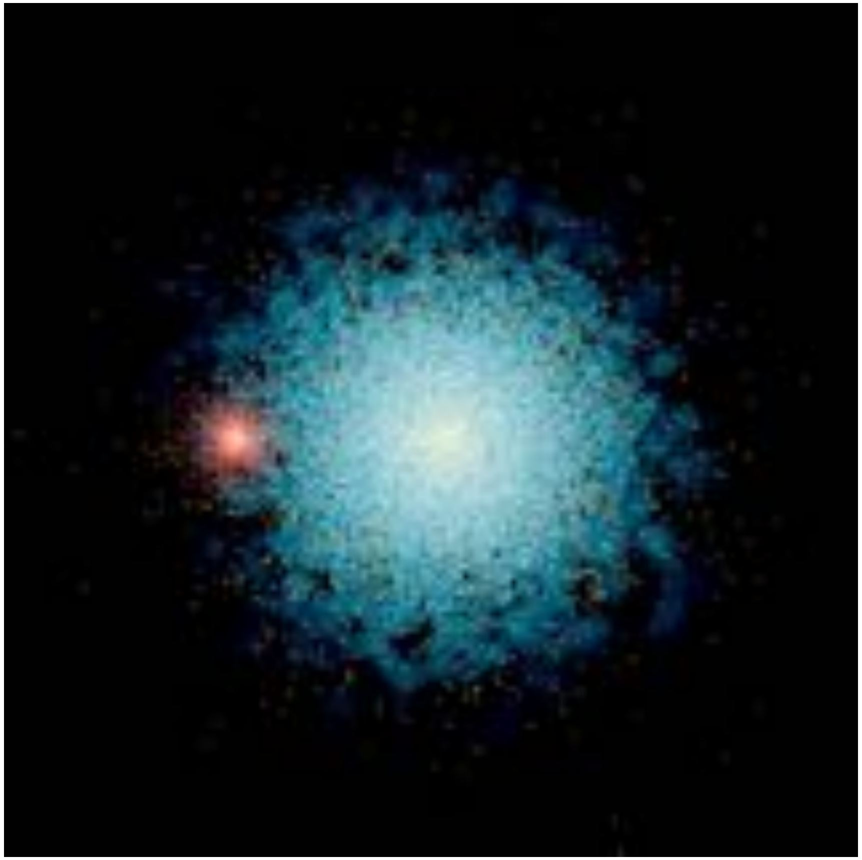
Steinmetz

Major mergers

Mihos & Herbquist

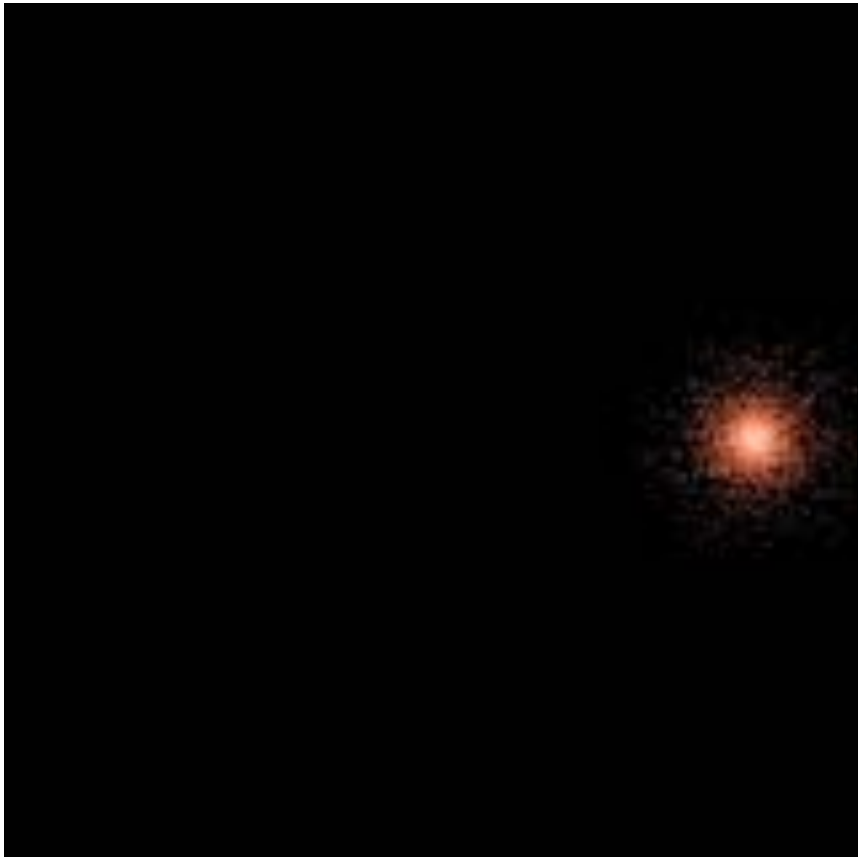
Minor merger





Mihos & Hernquist

Minor merger



Mihos & Hernquist