Astr 5465 March 2, 2020
Photometric Properties Galaxies: Ellipticals

- **Photometric Properties of Elliptical Galaxies**
  - **Surface photometry (e.g. GALFIT)**
    - **Requires accurate flat fields and sky subtraction**
    - **Mask stars and contaminants**
    - **Fit ellipses at (say) logarithmic surface brightness levels**
    - **Adopt average ellipticity and position angle**
    - **Compute projected radius for each image pixel and bin to create surface brightness profile**
  - **Rapid decrease in surface brightness with radius**
  - **De-projection via Abel integral equation**
    - **Few analytic pairs [I(R) vs. j(R)] exist**

Hubble Law:

$$I(R) = \frac{I_0}{\left(1 + \frac{R}{R_0}\right)^2}$$

de Vaucouleurs ($R^{1/4}$) law:

$$I(R) = I_e \exp\left(-7.67\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right]\right)$$

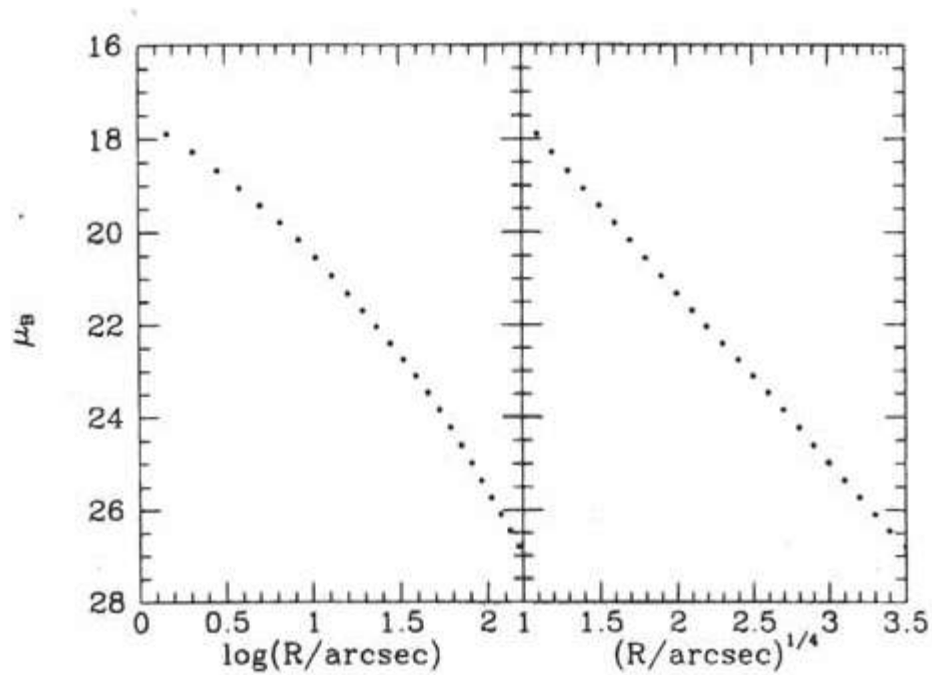
or in surface brightness (mags/arcsec^2):

$$\mu(R) = \mu(R_e) + 8.325\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right]$$

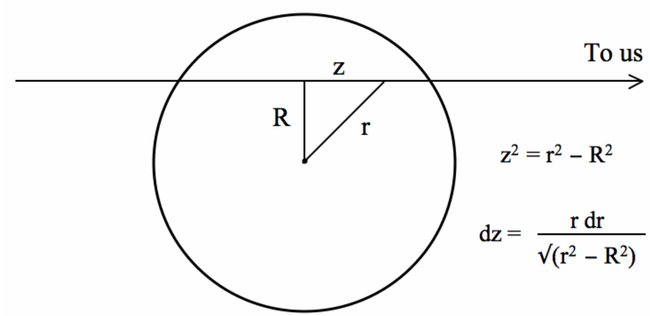
Sersic law (more general):

$$I(R) = I_e \exp\left(-b\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right)$$

where $b = 1.999\,n - 0.327 (N > 1)$



$$I(R) = \int_{-\infty}^{\infty} j(r)\, dz = 2\int_R^{\infty} \frac{j(r)\, r\, dr}{\sqrt{(r^2 - R^2)}}$$



$z^2 = r^2 - R^2$

$dz = \frac{r\,dr}{\sqrt{(r^2 - R^2)}}$

Photometric Properties of Ellipticals: Cores

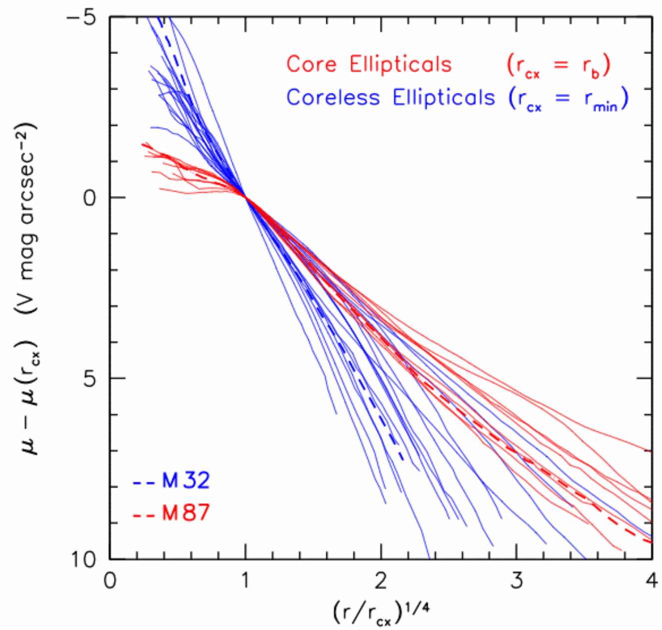
- Core Properties of Elliptical Galaxies
  - Fit cores and envelopes with separate power-law profiles
  - "Nuker" profiles (double power-law):
  - $I(R) = I_b 2^{(\beta-\gamma)/\alpha}(R/R_b)^{-\gamma}[1+(R/R_b)^{\alpha}]^{(\gamma-\beta)/\alpha}$
  - Power laws (diverge at R =0):

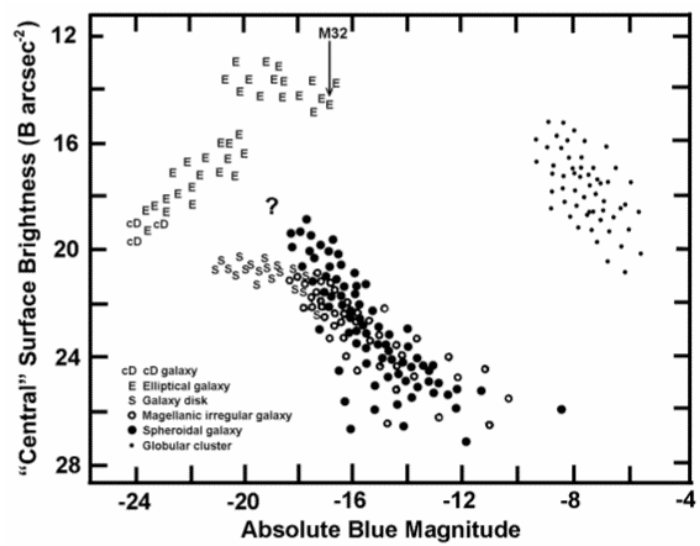
    $j(r) \sim r^{-1.9}$
  - Cuspy cores (breaks flatter at small R):

    j(r) ~ r-0.8
  - Power laws found in lower luminosity ellipticals

    $M_v > -20.5$
  - Cores found in higher luminosity ellipticals

    $M_v < -20.5$
  - Low luminosity dwarf spheroidals don't fit in
  - Dead irregulars?
- Kormendy's summary
  - Average surface brightness of Es falls with increasing luminosity
  - Dwarf spheroidal population distinct from classical elliptical galaxies
  - Globular clusters are not just small ellipticals.
    - •Much denser (more tightly bound)
    - •No dark matter?





Photometric Properties Galaxies: Spirals

- **Photometric Properties of Spiral Galaxies**
  - **Surface photometry**
    - **Fit ellipses at (say) logarithmic surface brightness levels**
    - **Adopt average ellipticity and position angle**
    - **Compute projected radius for each pixel and bin**
  - **Two components in SB profile**
    - **Bulge (elliptical-like)**
    - **Exponential Disk**
    - **Bulge-Disk decomposition**
    - **Color gradients**
  - **Model fits:**

For the bulge:

$$\mu(R) = \mu(R_e) + 8.325\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right]$$

Typical values for R_e are 0.5-4 kpc.

Integration of intensity yields:

$$L_{Total} = 7.22\pi R_e^2 I_e$$

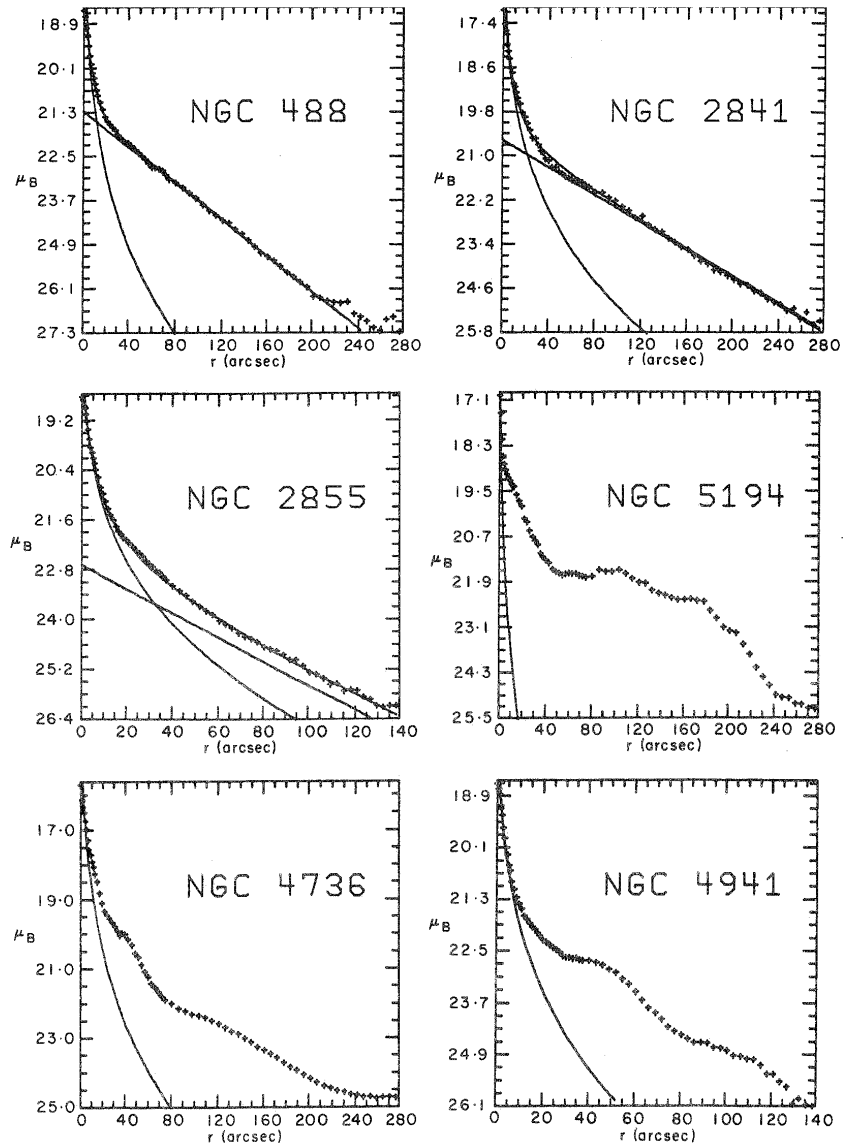
For the disk:

$$I(R) = I_0 \exp\left(\frac{-R}{R_d}\right) \quad \text{or}$$

$$\mu(\mathrm{R}) = \mu_0 + 1.086\left(\frac{R}{R_d}\right)$$

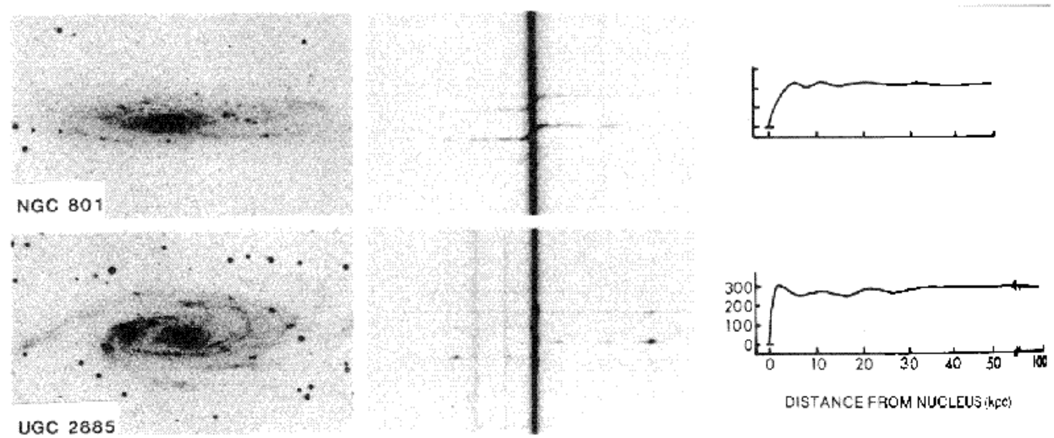
where R_d is the disk scale length.

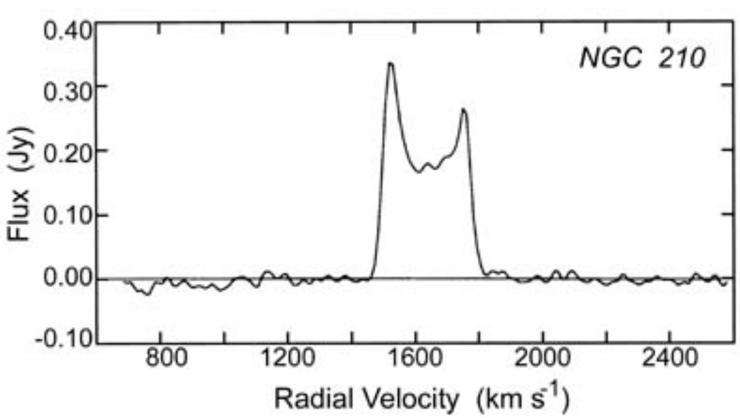
Typical values for R_d are 2 - 5 kpc.

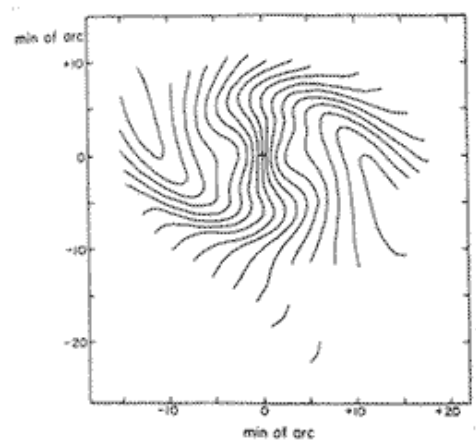


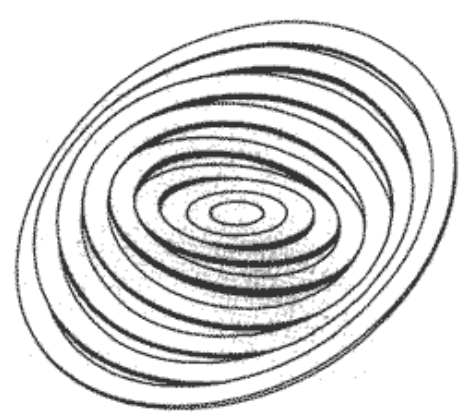
Kinematic Properties Galaxies: Spirals

- **Kinematic Properties of Spiral Galaxies**
  - **Rotation curves**
    - **One-dimensional slit spectra**
    - **Flat rotation curves (Rubin)**
  - **Two-dimensional velocity fields**
    - **21-cm velocity fields**
    - **Integrated spectra (Fisher & Tully)**
    - **Channel maps and Spider diagrams (Bosma)**
    - **ALMA will enable this in CO at high z**







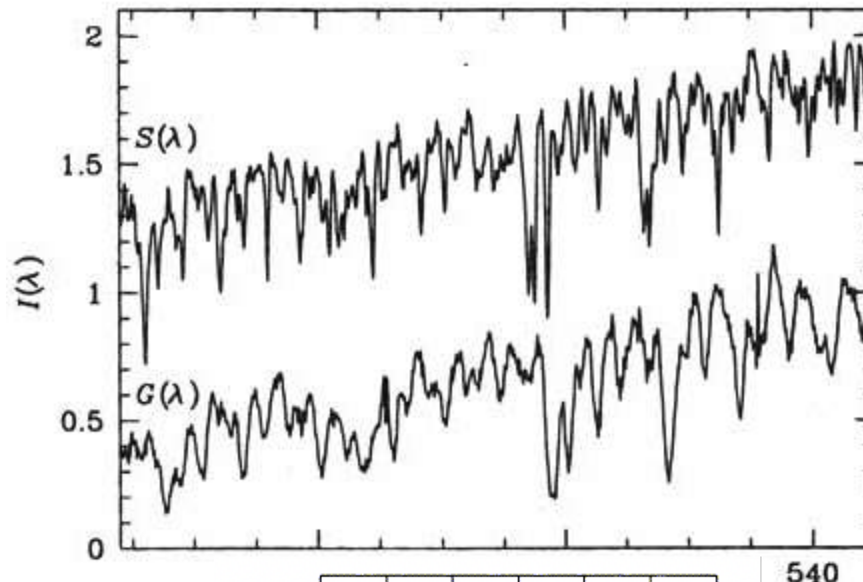


Kinematic Properties Galaxies: Ellipticals

- Velocity dispersions in ellipticals
  - Slit and fiber spectra
    - See Brault & White 1971 for General Application of FFTs to Spectroscopy
    - Template Fitting of Elliptical Spectra with Giant Star Spectra as Template
    - Absorption line spectra of Ellipticals
    - K-giant template spectra
    - Fourier quotient method
    - Fitting in Fourier Space

      (Sargent et al 1977)
    - Cross-correlation Method
    - Fitting in Real Space

      (Tonry and Davis 1981)
    - See IRAF XCORR documentation
    - Result is the Line-of-sight Velocity Distribution (LOSVD) function
  - Models
    - Most LOSVDs are well-fit with Gaussian so usually only dispersions are reported
    - Mapping from 2D IFUs is possible
    - Kinematically distinct cores
    - Substructure, etc.
    - Tensor Virial Theorm:
    - V_m/σ vs ellipticity implies flattening of elliptical is due to anisotropy (not rotationally supported)



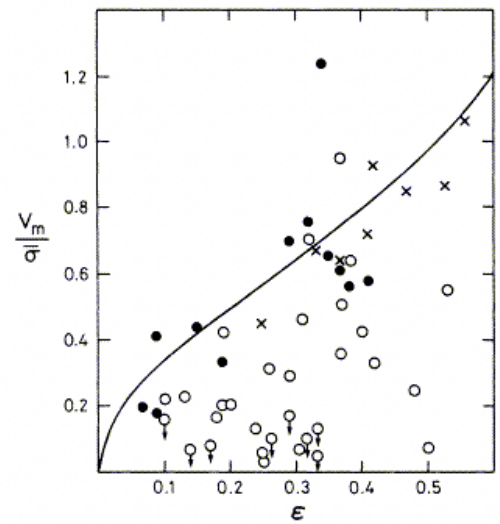
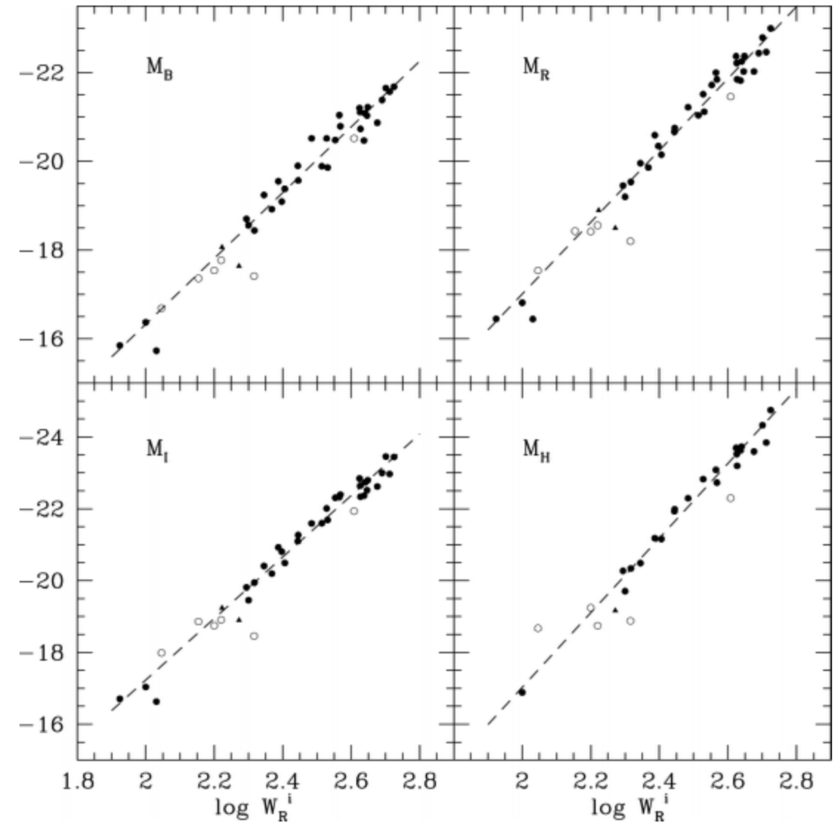


FIG. 3.—The quantity $V_m/\bar{\sigma}$ against ellipticity. Ellipticals with $M_B^{UH} > -20.5$ are shown as filled circles; ellipticals with $M_B^{UH} < -20.5$, as open circles; and the bulges of disk galaxies, as crosses. The solid line shows the $(V/\sigma, \epsilon)$-relation for oblate galaxies with isotropic velocity dispersions (Binney 1978).

Scaling Relations of Spiral Galaxies

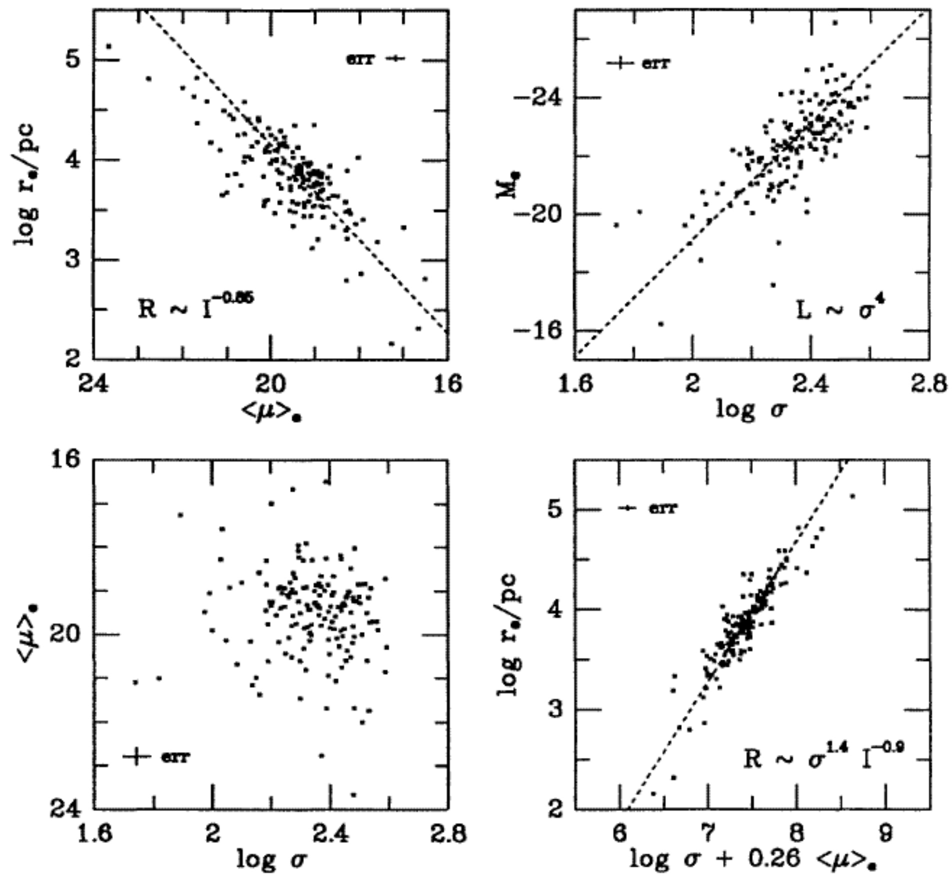
- **Tully-Fisher Relation**
  - **Empirical correlation between the amplitude of disk rotation curves and the luminosity of the galaxy.**
  - **Remarkable because it implies integrated star formation history is somehow regulated by the DM halo.**
    - **Star Formation Feedback?**
  - **Used to measure redshift-independent distances and to measure H_0**
  - **Should provide a measure of galaxy evolution since dark matter and luminous matter should evolve independently.**



(Pierce & Tully 1992)

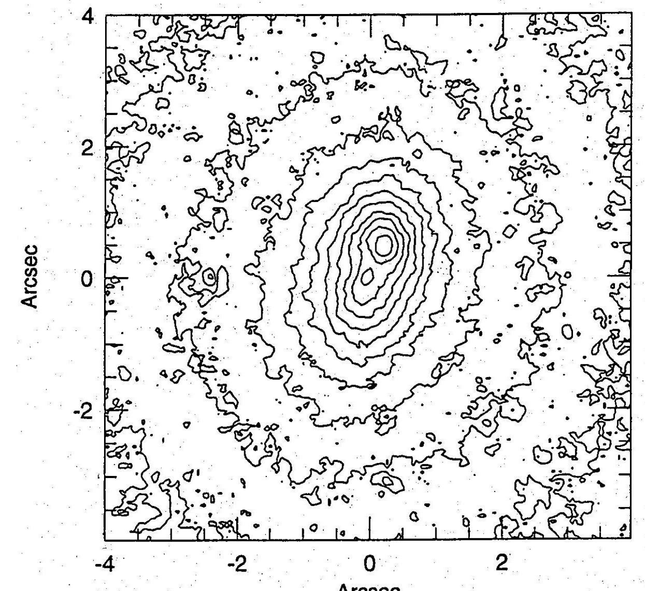
Scaling Relations of Elliptical Galaxies

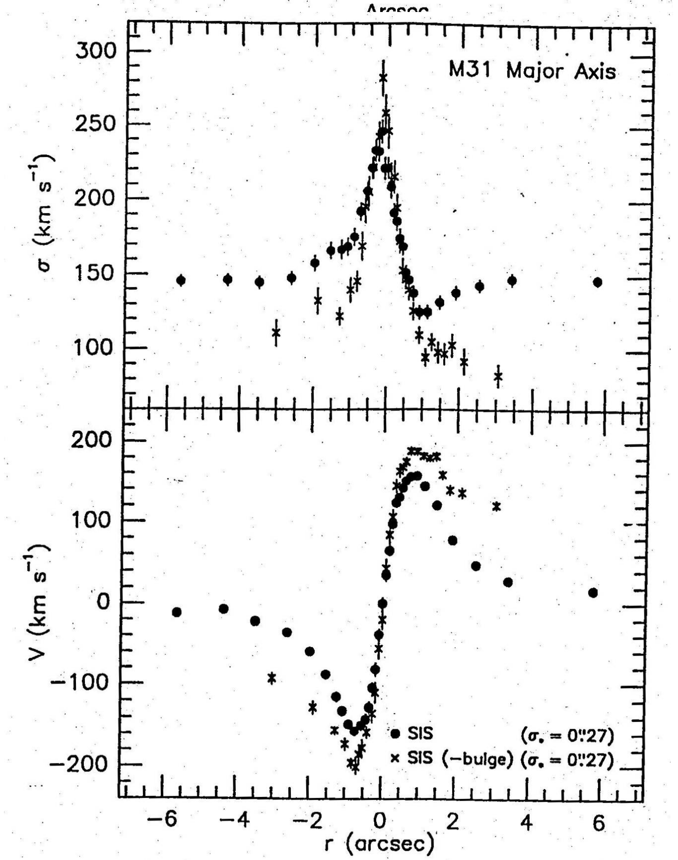
- **Fundamental Plane**
  - Ellipticals occupy a 3-d plane (Djorgovski & Davis 1987)
  - Predicted by the virial theorm
  - Projection of the plane can result in an indicator of distance
  - Similar to the Tully-Fisher relation but for ellipticals
  - Both relations are calibrated nearby using stars (more about this later) and then used to measure the Hubble Constant over large scales
  - Both relations can be applied at moderate/high redshift in order to parameterize the evolution of galaxies



Nuclei of Galaxies

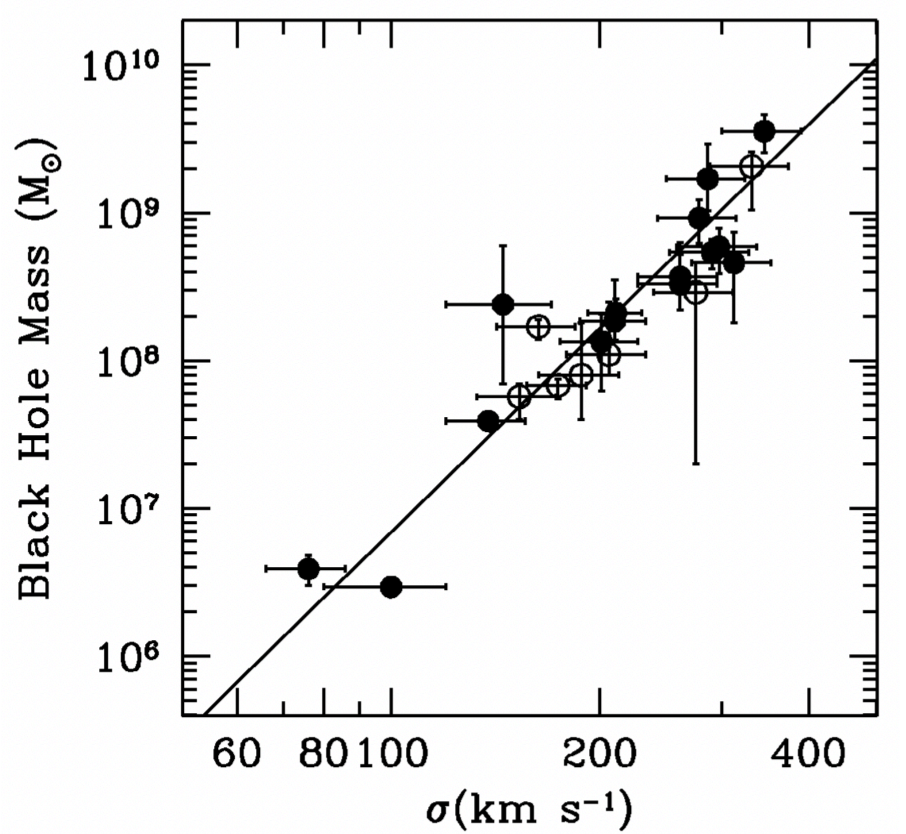
- **Active galactic Nuclei**
  - Existence of AGN invites investigation of galactic nuclei
  - Highly collimated jets and rapid variability implies small size of source.
  - More about this later but let's examine properties of nuclei
- **Nearness of M31 allows high spatial resolution**
  - Early work identified stellar object as nucleus
  - High spatial resolution imaging showed this to be an error
  - Nucleus is actually the low SB center of the outer isophotes
  - Stellar object is a nearly superimposed globular cluster
  - High resolution spectroscopy showed rapid rotation and a high velocity dispersion.
  - Evidence of a Super Massive Black Hole (SMBH)
- **HST provides relatively high resolution capabilities out to the Virgo Cluster (14 Mpc)**
  - All galaxies (elliptical and spirals) studied in sufficient detail to date show evidence for an SMBH





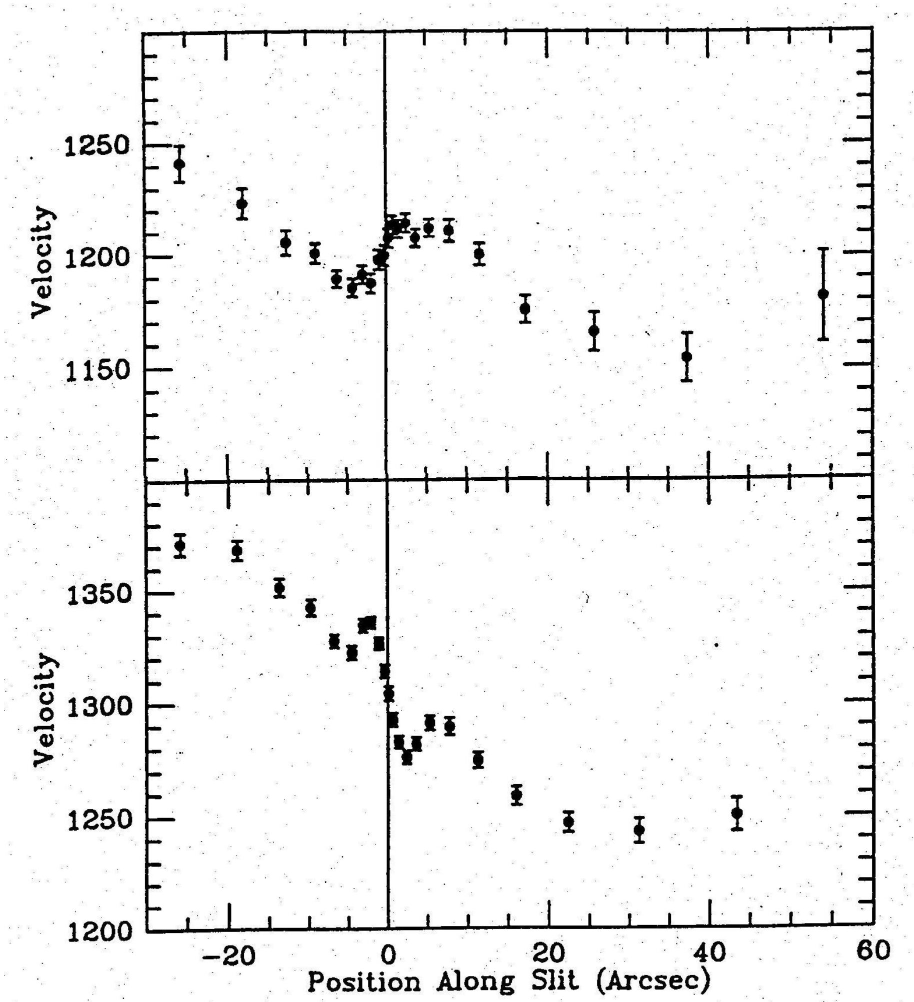
Nuclei of Galaxies

- Existence of SMBH suggests their formation requires residence in galactic nucleus (Ferrarese & Merritt 2000; Gebhardt et al. 2000)
  - BH must from from evolution of high mass stars
  - SMBH requires an efficient process for growth
  - Mergers and massive accretion?
  - BHs must form early (high z) and then merge/grow to become SMBHs
  - Low SB disk galaxies seem to have wimpy SMBHs (few mergers?)
- Mass of the SMBH correlates with the mass of the bulge
  - Growth tied together?
  - Mergers could drive both both the bulge growth and fuel the SMBH



Nuclei of Galaxies

- **Cores of Spiral Galaxies Can Be Complex**
- **Some spiral galaxies have distinct cores**
  - **Core has completely different rotational properties than remainder of galaxy**
  - **Implication is that a merger has driven gas and stars into the nucleus independent of the rest of the disk**
  - **Dynamical times of nucleus and disk are completely different**
  - **Nuclear material must be the more recent event**
  - **Effect seen in both gas (emission lines) and in stars (absorption lines)**
- **AGN jet axis often not aligned with spiral galaxy's rotation axis**
  - **Further evidence that nuclear formation and accretion are distinct from the remaining galaxy**



Some References

- "Nuker" Profiles: Lauer et al. 1995, AJ,110, 2622
- Composite Sersic Profiles: Trujillo et al. 2004 astroph/0403659
- Analysis and Restoration of Astronomical Data via the Fast Fourier Transform: Brault & White 1971, A&A 13, 169
- Fourier Transform and Its Applications: Bracewell (McGraw-Hill)
- Fundamental Plane of Elliptical Galaxies: Djorgovski & Davis 1987, ApJ 313, 50
- Tully-Fisher Relation: Tully & Fisher 1977, AA 54, 661