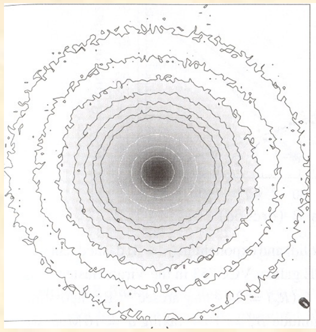
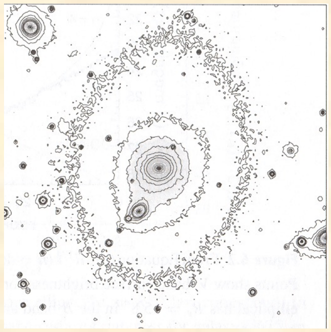
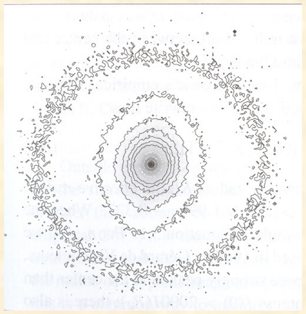
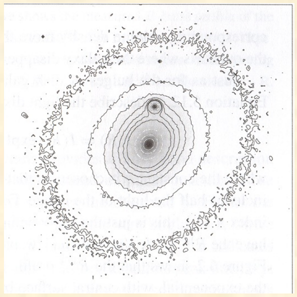



Photometry of Galaxies

- Basics
- Absolute Magnitudes
- Surface Photometry
- Sky Brightness
- Surface Brightness Profiles
- 3D Shapes
- Luminosity Functions
- Global Correlations

Basics of Photometry

- Magnitude System: For two stars or two galaxies :

$$m_1 - m_2 = -2.5\log\left(F_1/F_2\right)$$

- For a particular filter band pass, where T_λ is the filter response:

$$m = -2.5\log\left(\int_0^\infty T_\lambda\ F_\lambda\ d\lambda\right) + \text{const.}$$

Ex) To calibrate the V band in the Johnson UBV system, we find that for an A0 V star with apparent magnitude V = 0:

$F_\lambda(5500\ \text{Å}) = 3.75 \times 10^{-9}$ ergs s^{-1} cm^{-2} Å^{-1} (Allen, AQ, p. 387)

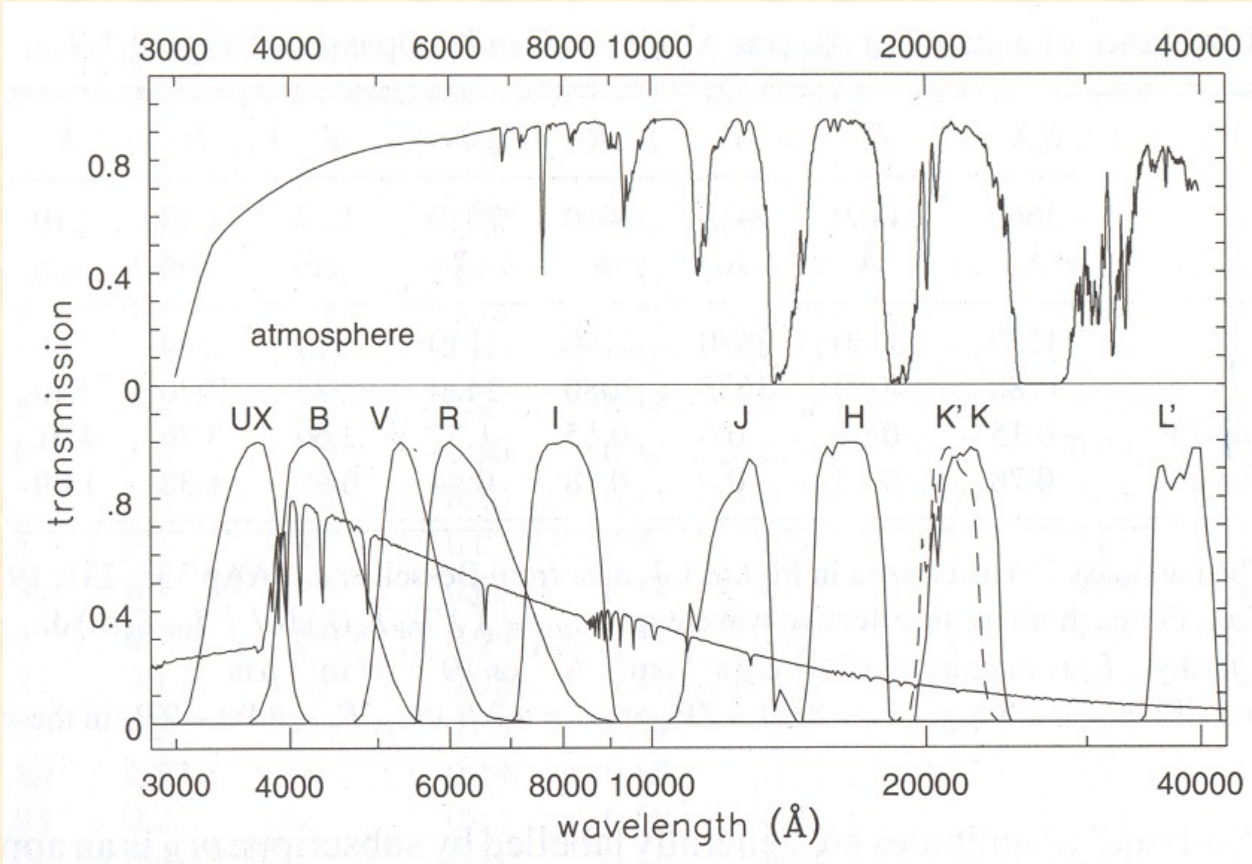
So: $V = -2.5\log[F_\lambda(5500\ \text{Å})] - 21.065$

- Colors: one filter magnitude minus another

Ex) B – V = 0 for A0 V star; bluer stars have negative colors

- colors (e.g., J – K) are defined to be zero for an A0 V star

Filter Bandpasses



(Sparke & Gallagher, p. 20)

Effective Wavelength : $\lambda_{eff} = \int_0^\infty \lambda T_\lambda d\lambda \Big/ \int_0^\infty T_\lambda d\lambda$

UX	B	V	R	I	J	H	K	L'
3660Å	4360Å	5450Å	6410Å	7980Å	1.22μ	1.63μ	2.19μ	3.80μ

Absolute Magnitudes – Galaxies

- Absolute magnitude (M): object's apparent magnitude at 10 pc
  - Measure of object's luminosity L (ergs s^{-1})
- Distance modulus: $m - M = 5 \log(d) - 5$ (d is distance in pc)
- Need to correct for extinction A (strongly λ dependent):

  Ex) $V - M_V = 5 \log(d) - 5 + A_V$
- For a high-redshift galaxy, correct for spectral shift in bandpass:

  Ex) $V - M_V = 5 \log(d) - 5 + A_V + K_V$
- In general, K is called the "K-correction"

  $K = k + 2.5 \log (1+z)$

  - k is a function of galaxy type and z (tabulated for different bandpasses in Frei & Gunn, 1994, AJ, 108, 1476)

- M_V (Sun) = +4.82 M_V (Galaxy) = – 20.6

Absolute Bolometric Magnitudes

- Measure of luminosity over entire spectrum:

$$M_{bol} = M = -2.5\log\left(\int_0^\infty L_\lambda d\lambda\right) + \text{const.}$$

Bolometric Correction:

$$BC = M - M_V \quad \text{(depends on object's spectrum)}$$

$$BC\ (\text{Sun}) = -0.08$$

- Some numbers (from Allen's AQ): ($\odot$ = Sun)
  - $M_\odot$ = +4.74
  - $L_\odot$ = 3.84 x 10^{33} ergs s^{-1}
  - L (Galaxy) ≈ 3.6 x 10^{10} $L_\odot$ (bolometric)
  - L_B (Galaxy) ≈ 2.3 x 10^{10} $L_\odot$ (B-band)
  - L_B (Galactic Disk) ≈ 1.9 x 10^{10} $L_{B\odot}$ (B-band)
  - $\mathcal{M}ass$ (Galactic Disk) ≈ 1 x 10^{11} $\mathcal{M}_\odot$ (to R = 8.5 kpc)
  - $\mathcal{M}/L_B$ (Disk) ≈ 5 $\mathcal{M}_\odot/L_{B\odot}$

Surface Photometry

- Surface brightness: I (ergs s^{-1} cm^{-2} $arcsec^{-2}$), μ (mag $arcsec^{-2}$)
- Independent of distance (d) to 1st order (neglecting cosmological redshift effects and surface brightness changes)
  - Consider a small patch of a galaxy with uniform brightness, sides of length D, apparent angular length α, at a distance d:

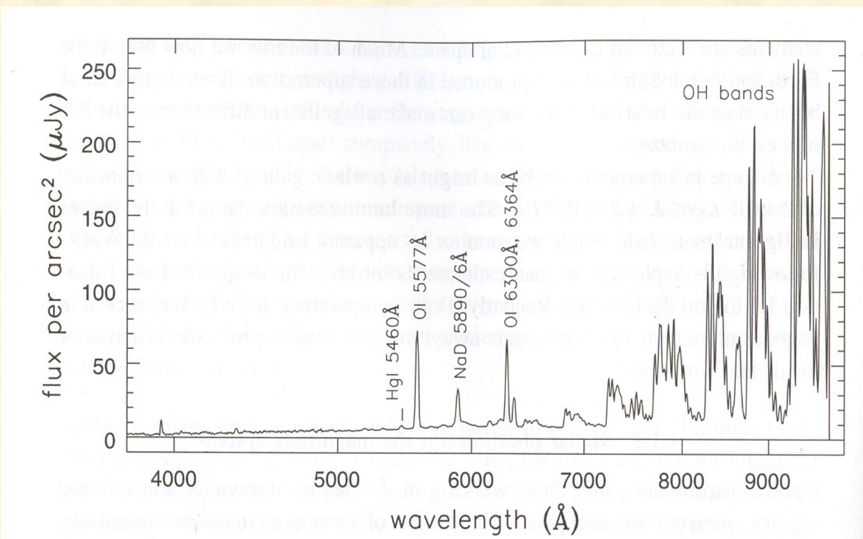
$$I = \frac{F}{\alpha^2} = \frac{L/4\pi d^2}{(D/d)^2} = \frac{L}{4\pi D^2}$$

  - For a flat disk, I increases as 1/cos(i) (i = inclination)
- *Measured* I depends on resolution of image
- Surface brightness profile: change in I with distance from center along major axis of image
  - Often measured by fitting elliptical isophotes.
  - Strongly affected by subtraction of night sky emission.
  - Core affected by PSF of telescope and "seeing".

Sky Brightness

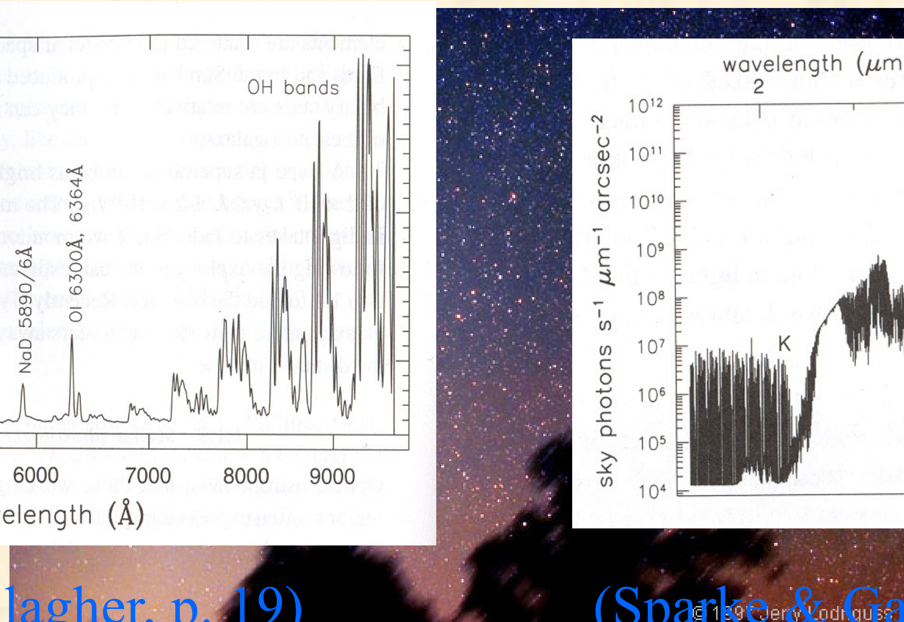
- For a dark sky (from the ground): $\mu_B \approx 23$, $\mu_R \approx 21$ mag arcsec^{-2}
- Contributions (decreasing importance in the optical):
  1) Zodiacal light: sunlight scattered off interplanetary dust
  2) Airglow: emission lines in the upper atmosphere (O I, NaD: UV ionization and recombination, excited OH: $O_3 + H_2O$ reaction)
  3) Unresolved Galactic starlight
  4) Diffuse extragalactic light

Optical Airglow

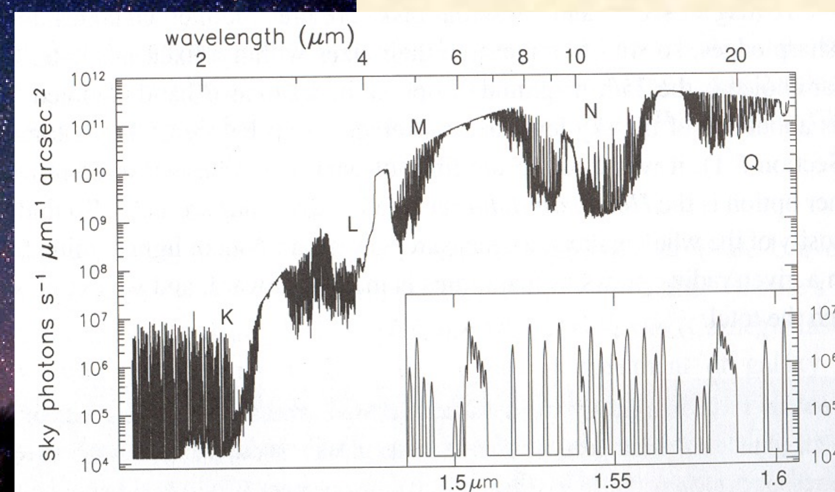


(Sparke & Gallagher, p. 19)

Zodiacal Light

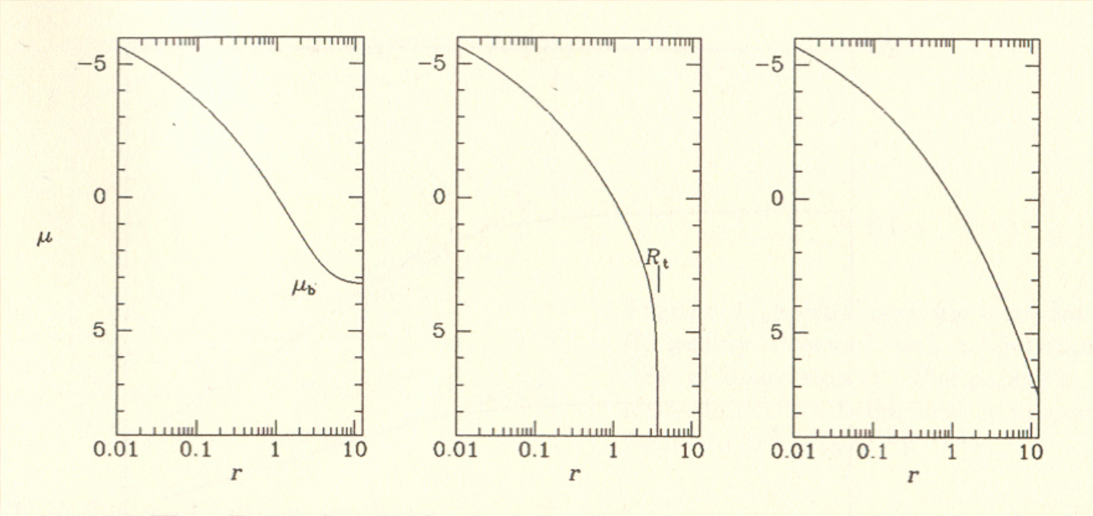


Infrared Airglow



(Sparke & Gallagher, p. 44)

Effects of error in sky subtraction:



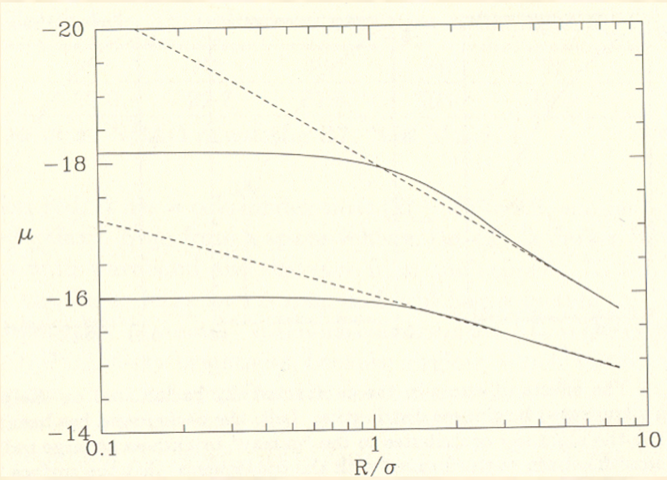
under over correct

(BM, p. 175)

Effects of PSF due to telescope + seeing:

$\mu \sim R^{-1}$

$\mu \sim R^{-0.5}$

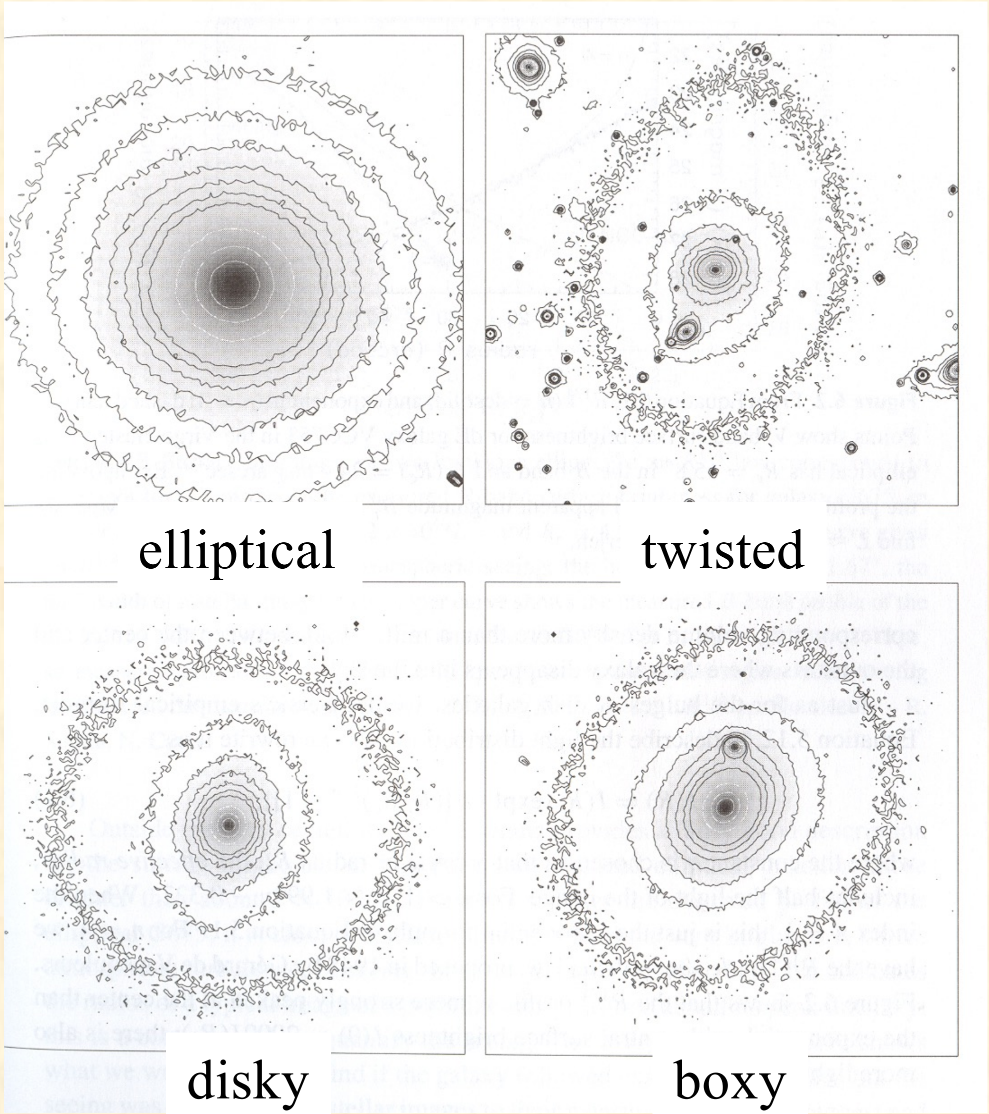


(BM, p. 176)

σ = dispersion of Gaussian PSF

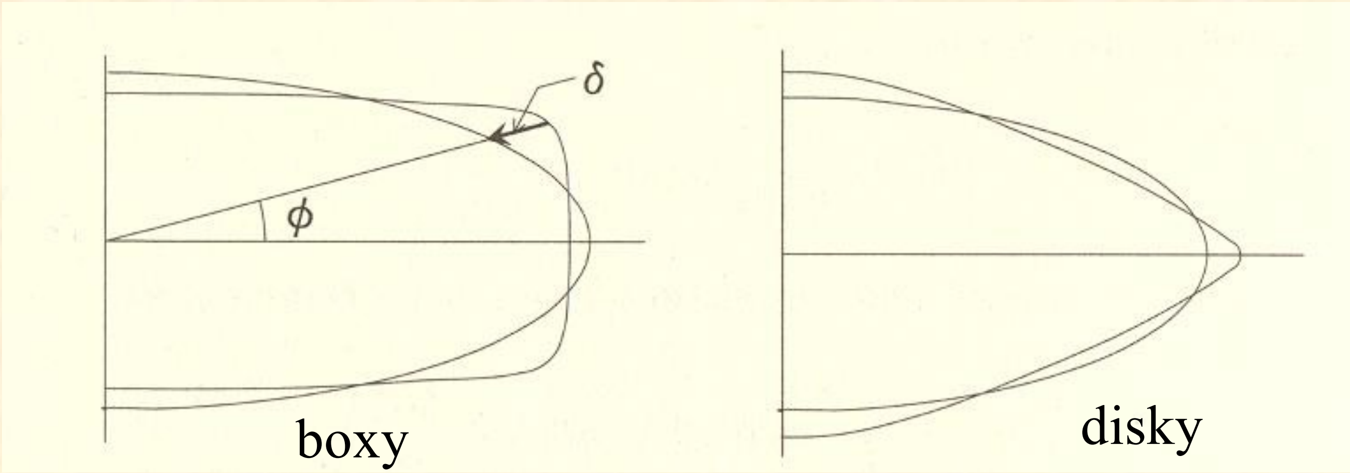
Elliptical Galaxy Isophotes

(Contours of equal μ_R)



(Sparke & Gallagher, p. 243)

- Boxy/disky isophotes often characterized by parameter a_4
- Fit elliptical isophotes and then measure δ as fct. of Φ



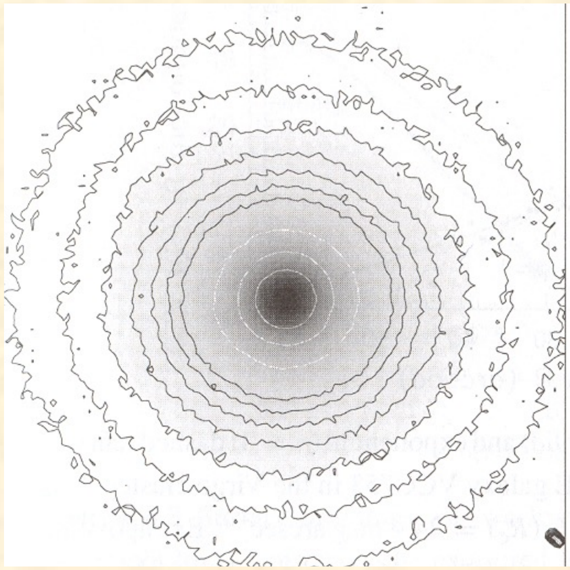
Express δ as a Fourier series:

$$\delta(\phi) = <\delta> + \sum_{n=1}^{\infty} a_n \cos(n\phi) + \sum_{n=1}^{\infty} b_n \sin(n\phi)$$

- Observational results: most a_n and b_n are negligible, except a_4
- $a_4/a < 0 \rightarrow$ boxy, $a_4/a > 0 \rightarrow$ disky (typical range: $-0.02 \rightarrow +0.02$)

Galaxy Sizes

- Isophotal radius: distance from center at which a particular surface brightness is reached along the semi-major axis
  - De Vaucouleurs radius (R_{25}): R at $\mu_B = 25$
  - Holmberg radius: R at $\mu_B = 26.5$
- Effective radius (Re): radius inside of which ½ of the light is emitted (depends on a model fit to brightness profile)



Ellipticals/Bulges: Surface-Brightness Profiles

- Often fit with the de Vaucouleurs $R^{1/4}$ law:

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

- Note this is of the form: $\mu = a - bR^{1/4}$ (a and b are consts.)

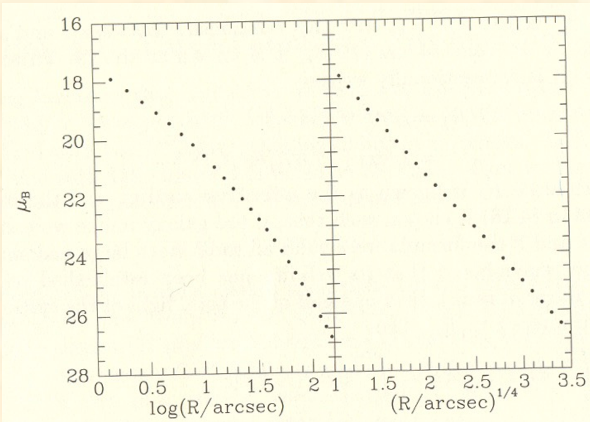
  → R = angular distance from the center

- ½ of the light is emitted inside R_e if the galaxy is circularly symmetric
- Elliptical galaxies typically have values a_e and b_e

  → $R_e = (a_e b_e)^{1/2}$ (½ light is inside ellipse with area πR_e^2)

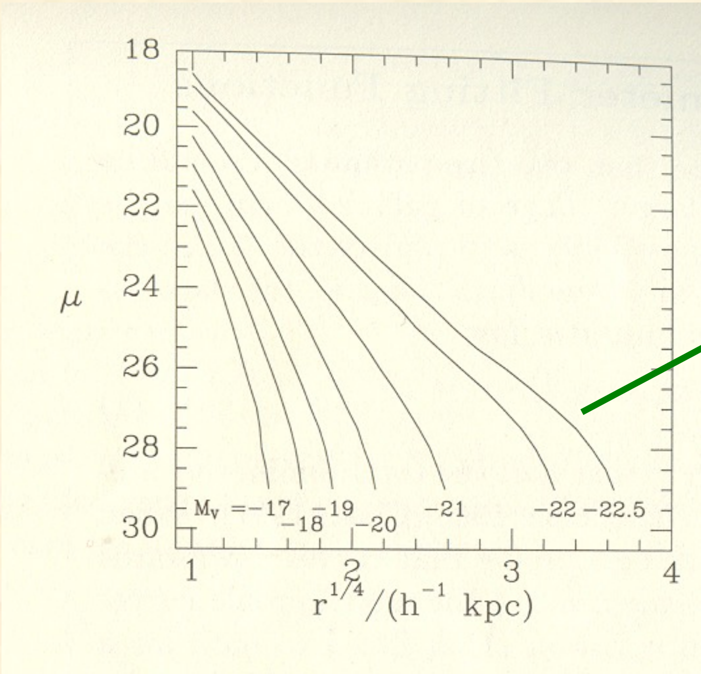
Ex) NGC 1700 (BM, p. 185)

Single power-law: ($I \sim R^{\alpha}$) doesn't fit.

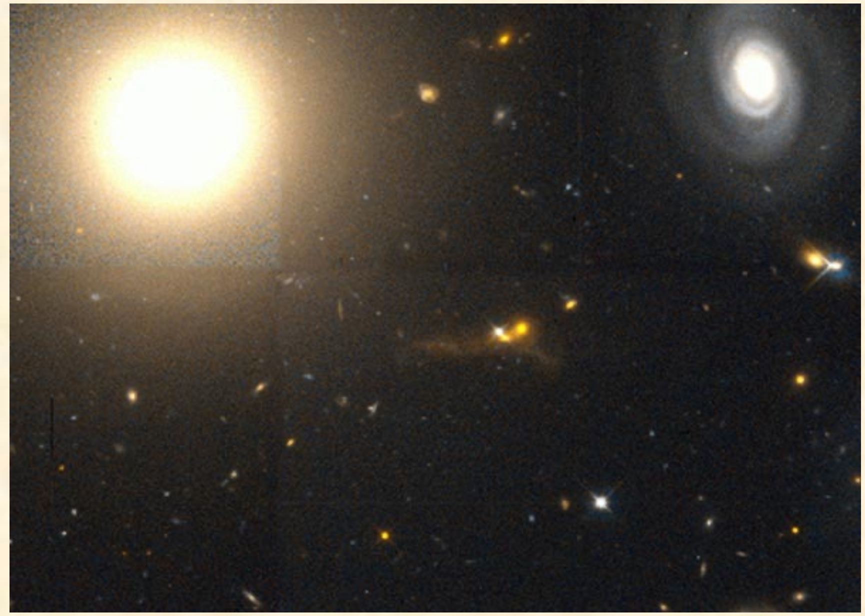


De Vaucouleurs law works well.

Deviations from $R^{1/4}$ in E's– Function of Luminosity



(BM, p. 175)

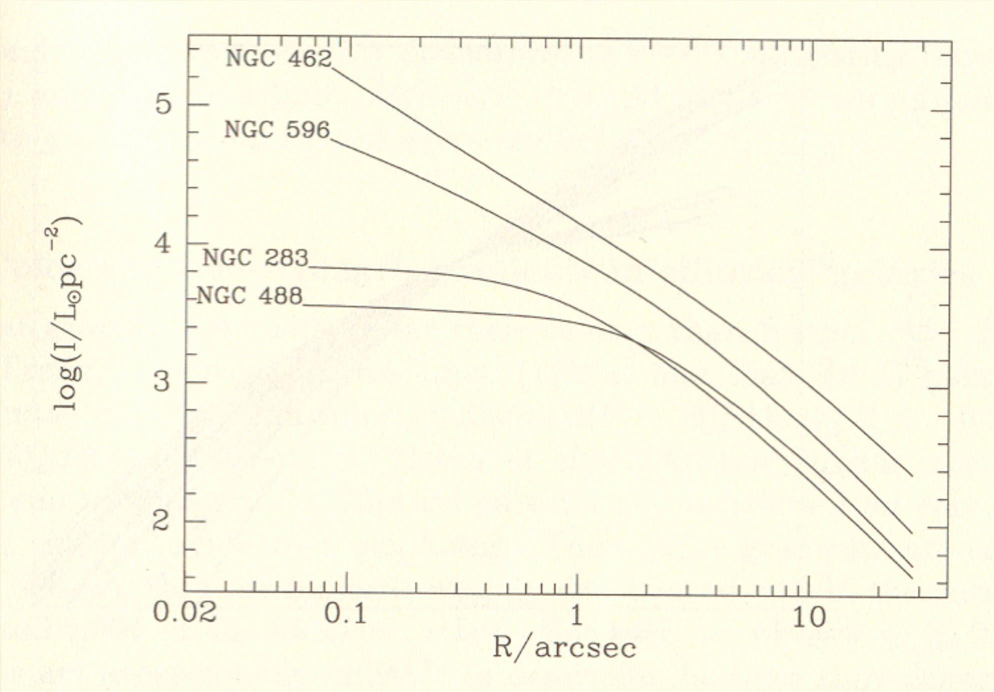


(HST/WFPC2 image of cD NGC 4881 in the Coma cluster, courtesy STScI)

- Two classes of dwarf Ellipticals (Kormendy & Djorgovski 1989):
  - Compact (M32): at low luminosity end of above graph
  - Diffuse: Best fit by exponential law: $I(R) = I_d \exp(-R/R_d)$ (much flatter than $R^{1/4}$)

Centers of Ellipticals (using *HST*)

- Surface brightness shows wide variation inside of 1".



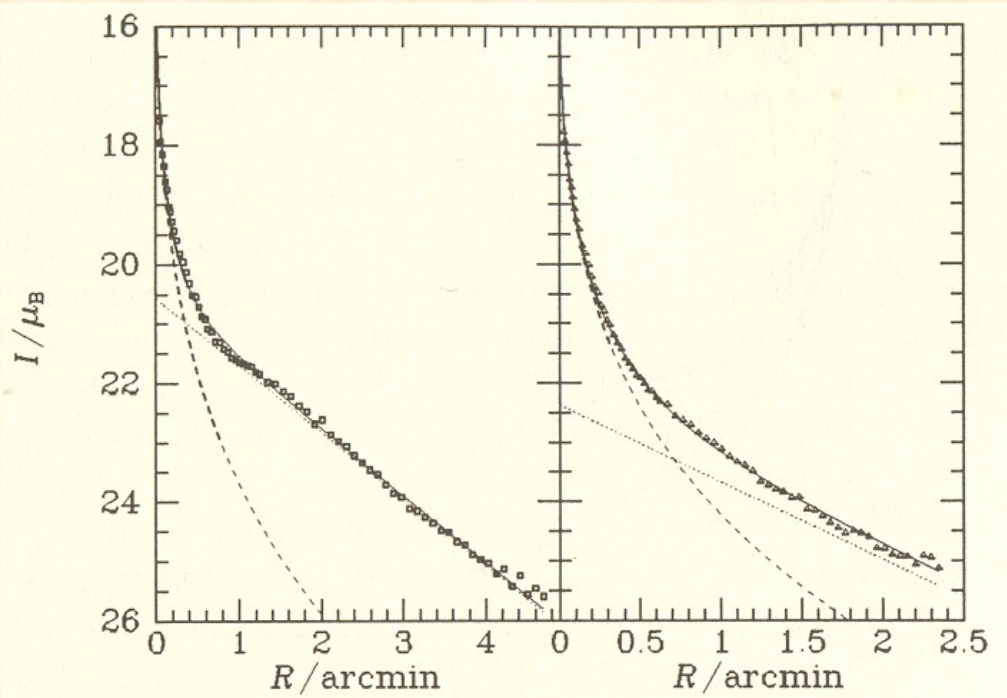
(BM, p. 191)

- Are cuspy profiles evidence for supermassive black holes?
  - Argument: BH's produce cuspy potentials and hence cuspy profiles (Lauer et al. 1991, 1992)

No - black hole masses from kinematics show no correlation with "cuspiness" (Kormendy & Richstone, 1995, ARAA, 33, 585-586)

Disks: Surface-Brightness Profiles

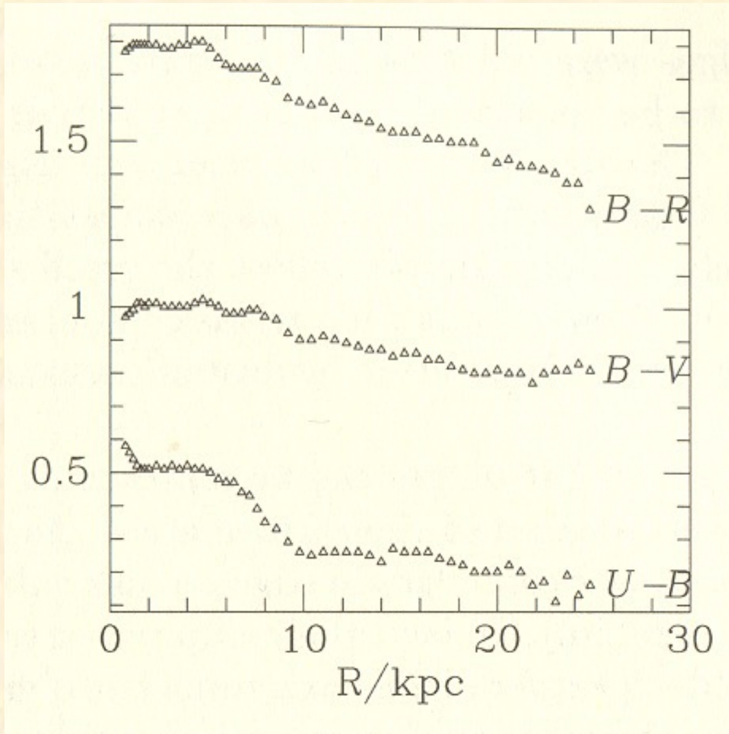
- Disks: Exponential law works: $I(R) = I_d \exp(-R/R_d)$
  - Most disk galaxies have R_d in the range 1- 10 kpc
- Complications with surface photometry:
  - Bulge overlap, bars, dust lanes, spiral arms, young stars
  - Use red or near-IR if possible.



Combined disk/bulge fit

(Binney & Merrifield, p. 216)

Color Gradients – M31



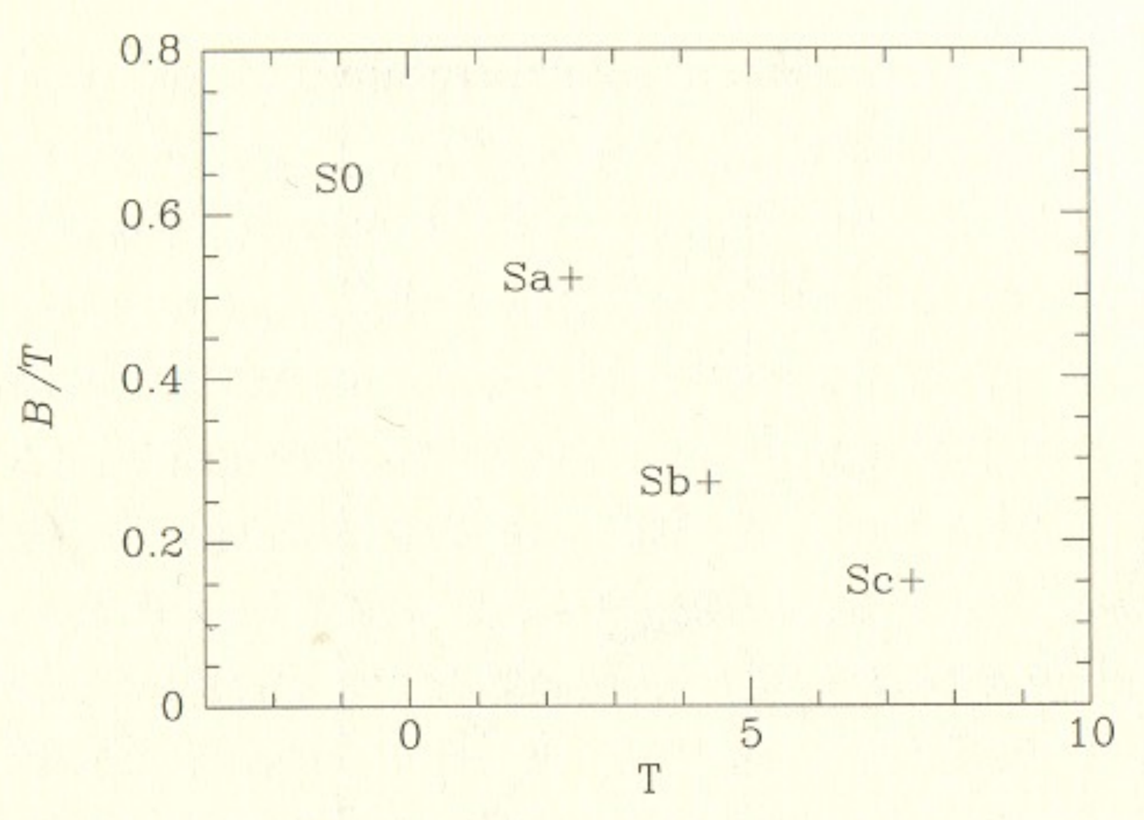
(Binney & Merrifield, p. 224)

- Spirals tend to get bluer with increasing distance from nucleus (as do ellipticals). Some combination of:
  1) Increasing # of hot, young stars.
  2) Decreasing metallicity.
- Exception: Starburst ("H II") galaxies have rapid ongoing star formation in their nuclei.

Bulges: Quantitative Correlation with Spiral Type

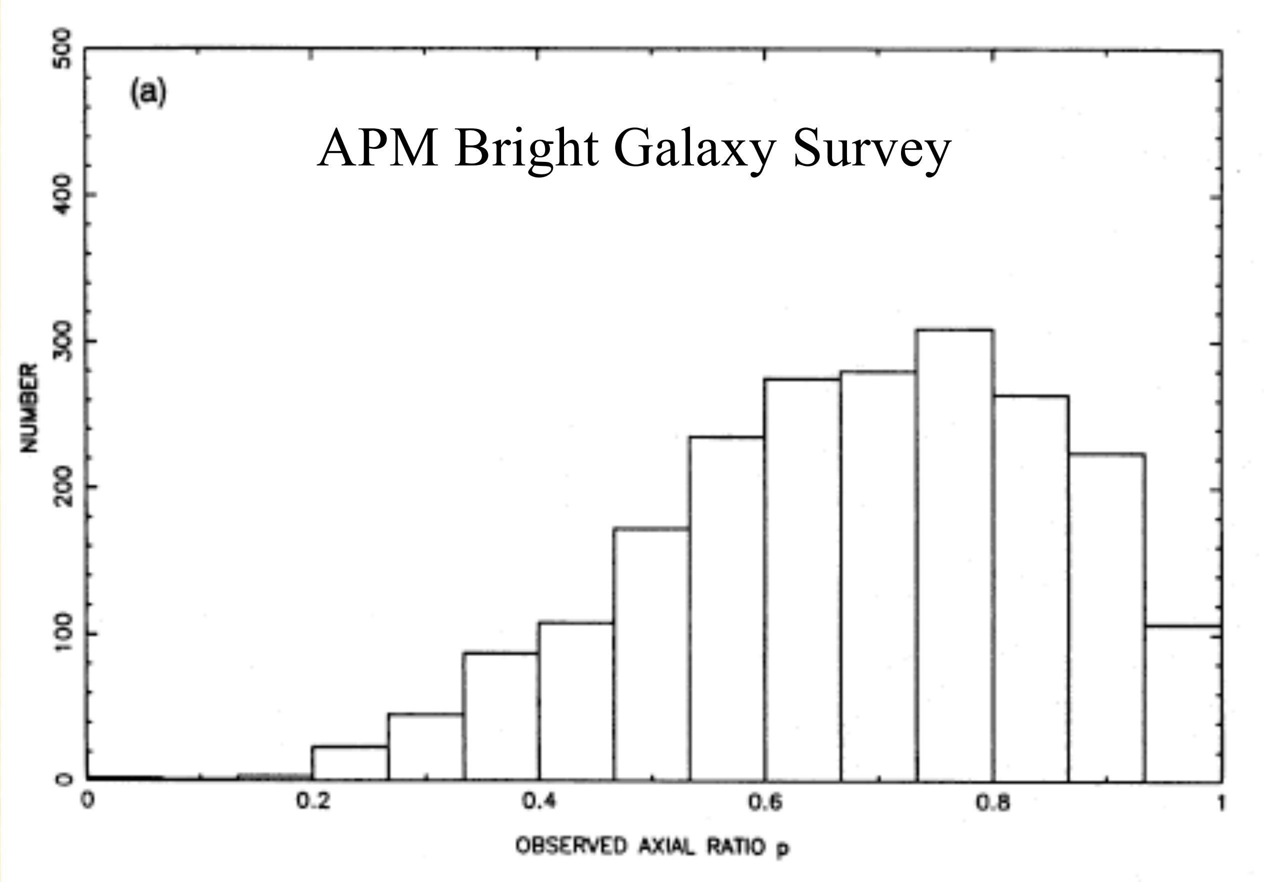
- Ratio of bulge to total luminosity from fits:

$$B / T = \frac{R_e^2 I_e}{R_e^2 I_e + R_d^2 I_d} = \frac{\text{bulge luminosity}}{\text{total luminosity}}$$



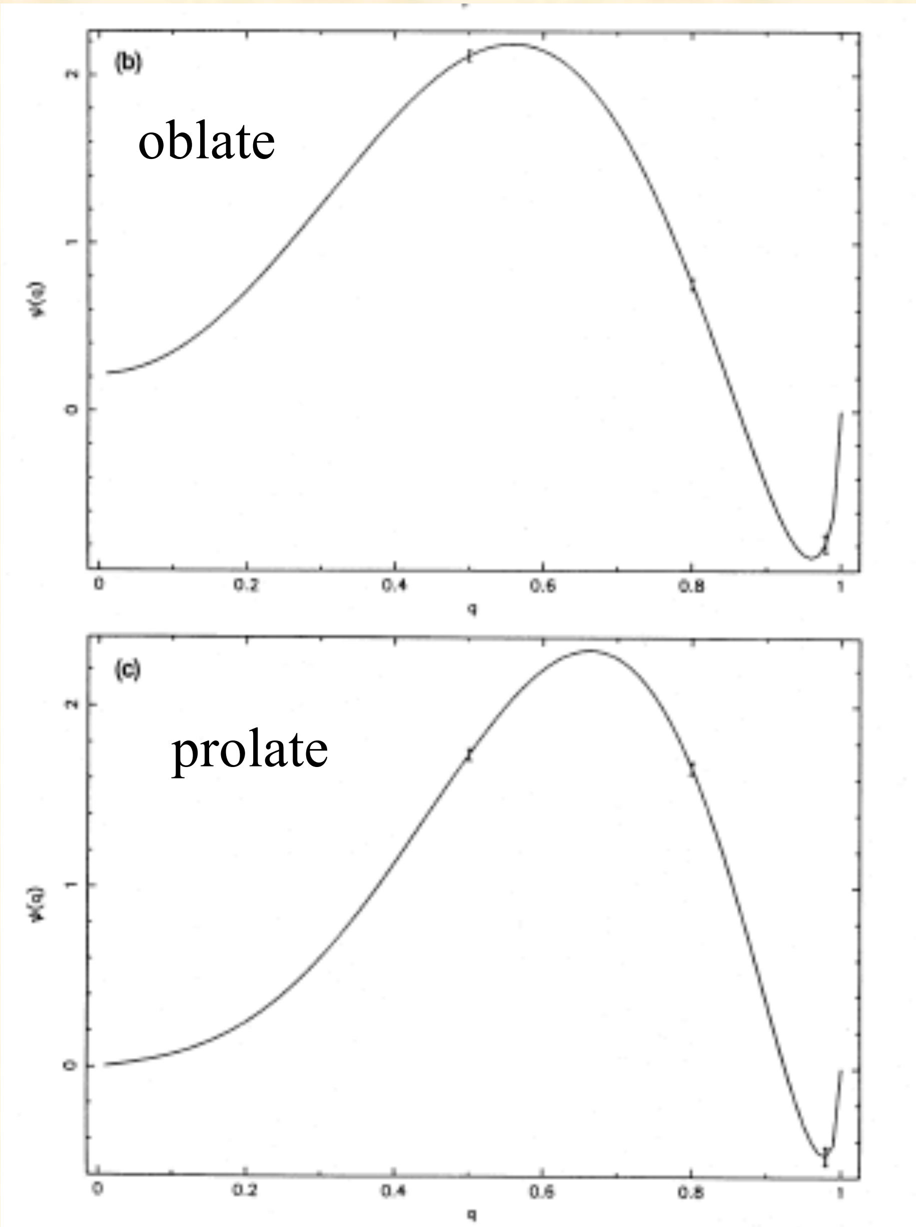
(Binney & Merrifield, p. 220)

True Shapes - Ellipticals



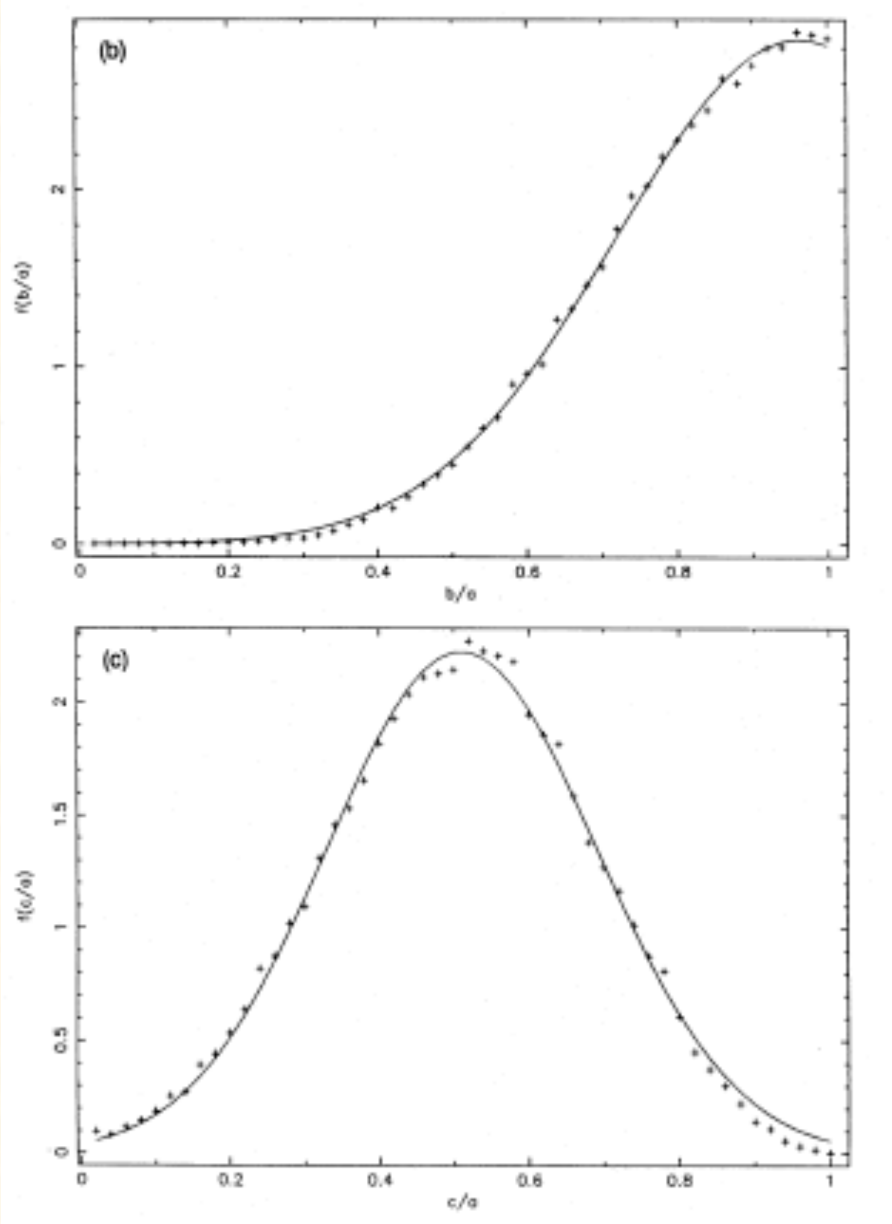
(Lambas et al. 1992, MNRAS, 258, 404)

- Assuming 3 axes of symmetry, are ellipticals oblate (a = b, c < a), prolate (a = b, c > a), or triaxial (a ≠b ≠c)?
- Need statistical studies of a large sample and assume that ellipticals are oriented randomly.



(Lambas et al. 1992)

- From observed distribution of axial ratios $\phi(p=b_{obs}/a_{obs})$, one can determine the true distribution for $\Psi(q = c/a)$ for oblate and prolate spheroids (Fall & Frank, 1993, AJ, 88, 1626)
- Both are unrealistic, since they give negative values at large q (spheres)
- Many ellipticals are likely *triaxial.*



(Lambas et al. 1992)

- For triaxials, need to assume an underlying distribution (e.g., Gaussian)
- Ellipticals tend to be more *oblate rather* than *prolate.*
- Luminous E' s tend to be more triaxial (i.e., more asymmetric) than fainter ones (Tremblay & Merritt 1996).

Bulges

- Bulges: "true" ellipticity: (major-minor)/major axis = 0 to 0.7
  - Flat bulges rotate more rapidly and have shallower brightness profiles → "pseudobulges"
  - ~25% have boxy or even "peanut" appearance.
  - Would be seen as roughly elliptical from other angles

NGC 5746

Disks

- Even "face-on disks" can be slightly elliptical (e up to ~0.04).
  - could be real or could be influence of spiral structure
- Surface brightness perpendicular to disk: use edge-on galaxies

  → $I(z) = I(R)\exp(-z/z_0)$ ($z_0 = 0.01$ to $0.1R_d$)
- Luminosity density:

  $j(r,z) = j_0 \exp(-r/r_d)\exp(-|z|/z_0)$ (double exponential)
- Most disks (like MW) have several components:

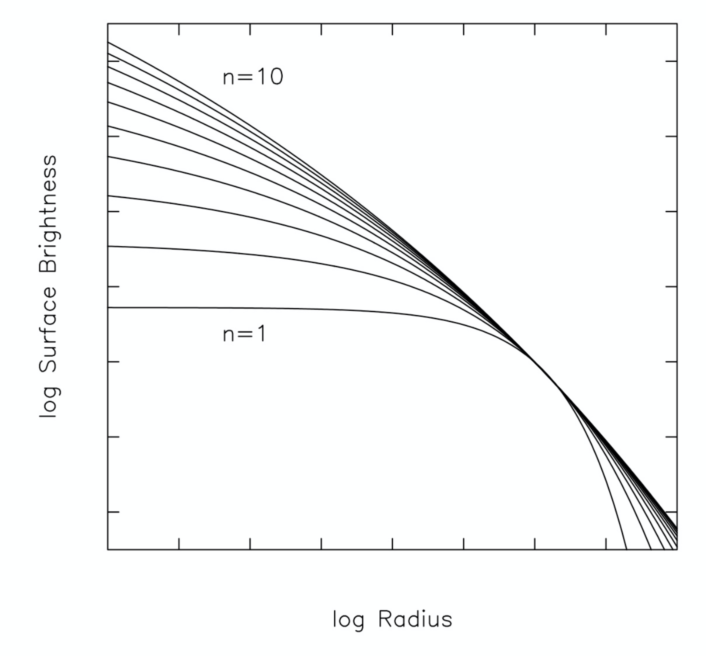
  Ex) Optical and near-IR photometry of IC 2531 (Wainscoat et al. 1989): 3 components

  1) Thick disk, $B - V = 0.78$, $z_0 = r_d/12$
  2) Thin disk, $B - V = -0.04$, $z_0 = r_d/96$
  3) Dust disk, $z_0 = r_d/48$

Sersic Brightness Profile

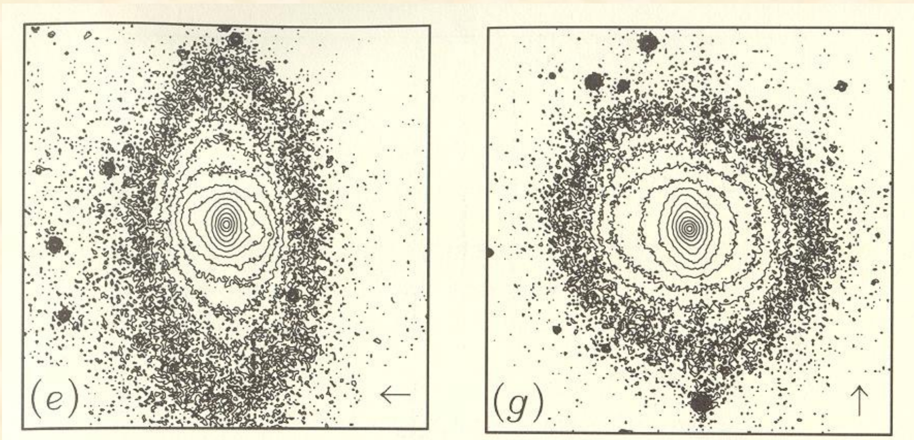
$$I = I_e \exp\{-b_n[(R / R_e)^{1/n} - 1]\}$$

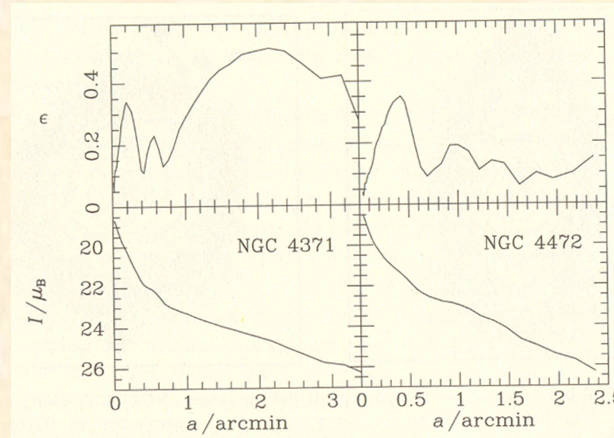
- b_n chosen so that ½ luminosity inside R_e
- n = 4 → de Vaucoulers law, n = 1 → exponential
- pseudobulges – between 1 and 4
- How many free parameters? → 3



Bars

- Bars: detected as deviation in ellipticity and bumps in brightness profiles





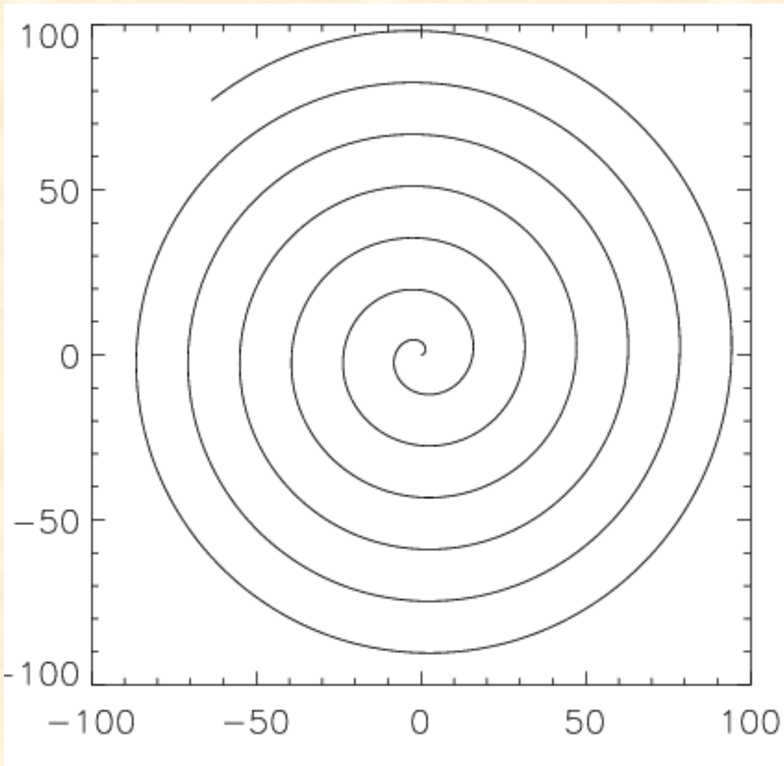
(Binney & Merrifield, p. 229, 230)

- Vertical structure: difficult to know, since bars can't be detected in edge-on galaxies
- Dynamical simulations: thin bars are unstable; tend to form peanut shapes with vertical dimensions similar to thick disk
- 75% of SBs have inner rings → bars, peanut-shaped bulges, and inner rings are somehow dynamically connected

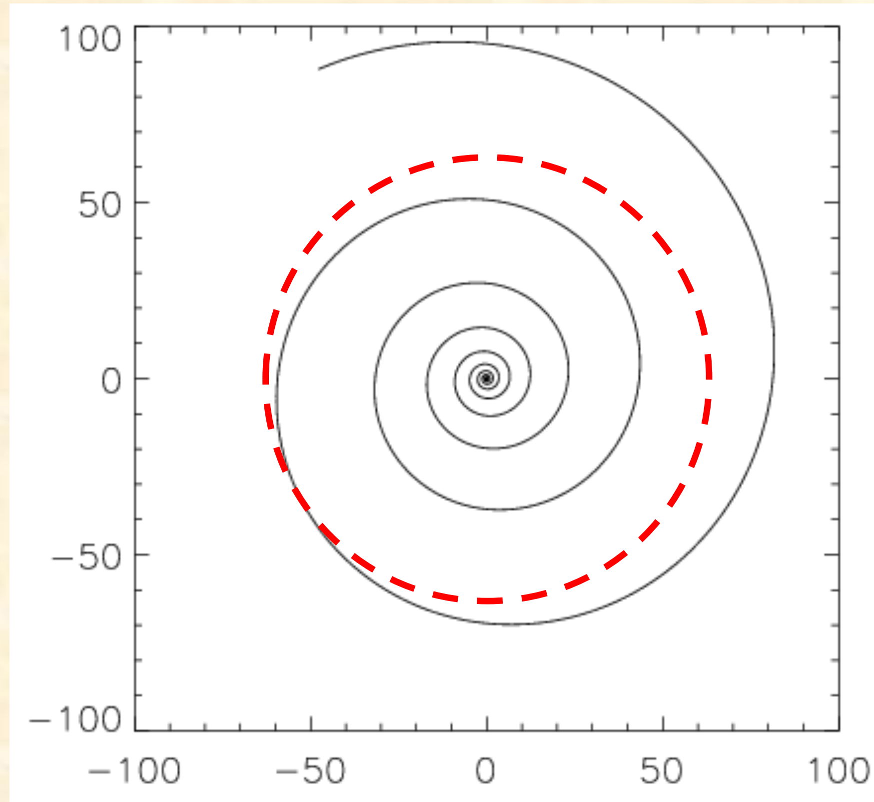
Spirals

- Tend to be logarithmic in shape: θ ~ ln (R) (polar coords.)

θ ~ R



θ ~ ln (R)



Pitch angle (ψ) = angle between arm and tangent to circle at R
- ranges from 5° (Sa) to 30° (Sc to Sd)

Spirals

- Bluer than surroundings → active star formation
- ~10% are grand design: tend to have a bar and/or outer satellite (M51)
- Kinematics: Spiral arms rotate as if they are "winding up".

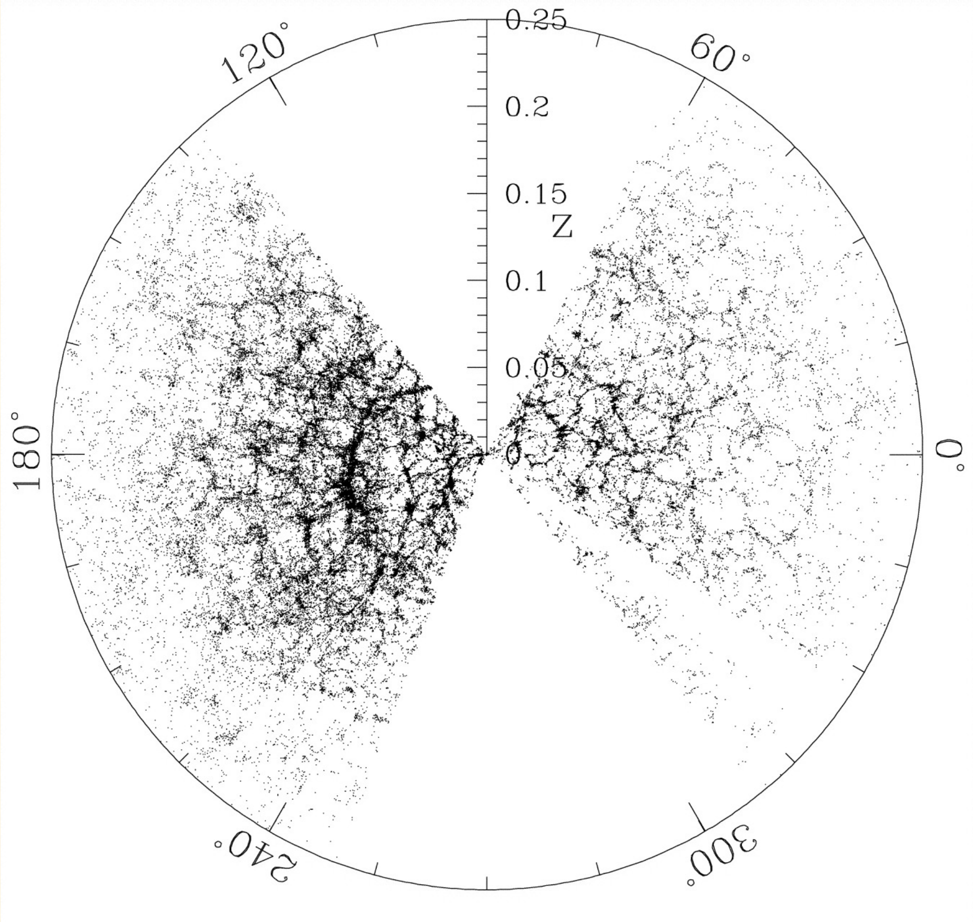
How can you tell which side of a spiral galaxy is closer?

→ Take a spectrum to get radial velocities + spiral arms wind

Another way to tell which side is closer

Near side occults bulge (works for more edge-on spirals)

Galaxy Luminosity Functions



(SDSS Wedge (Blanton, et al. 2003, ApJ, 592, 819)

- How do we get the # of galaxies at each luminosity?
- Need imaging + spectroscopic surveys (e.g. SDSS, 2DF)
- Integrate surface brightness →flux, z →distance, luminosity

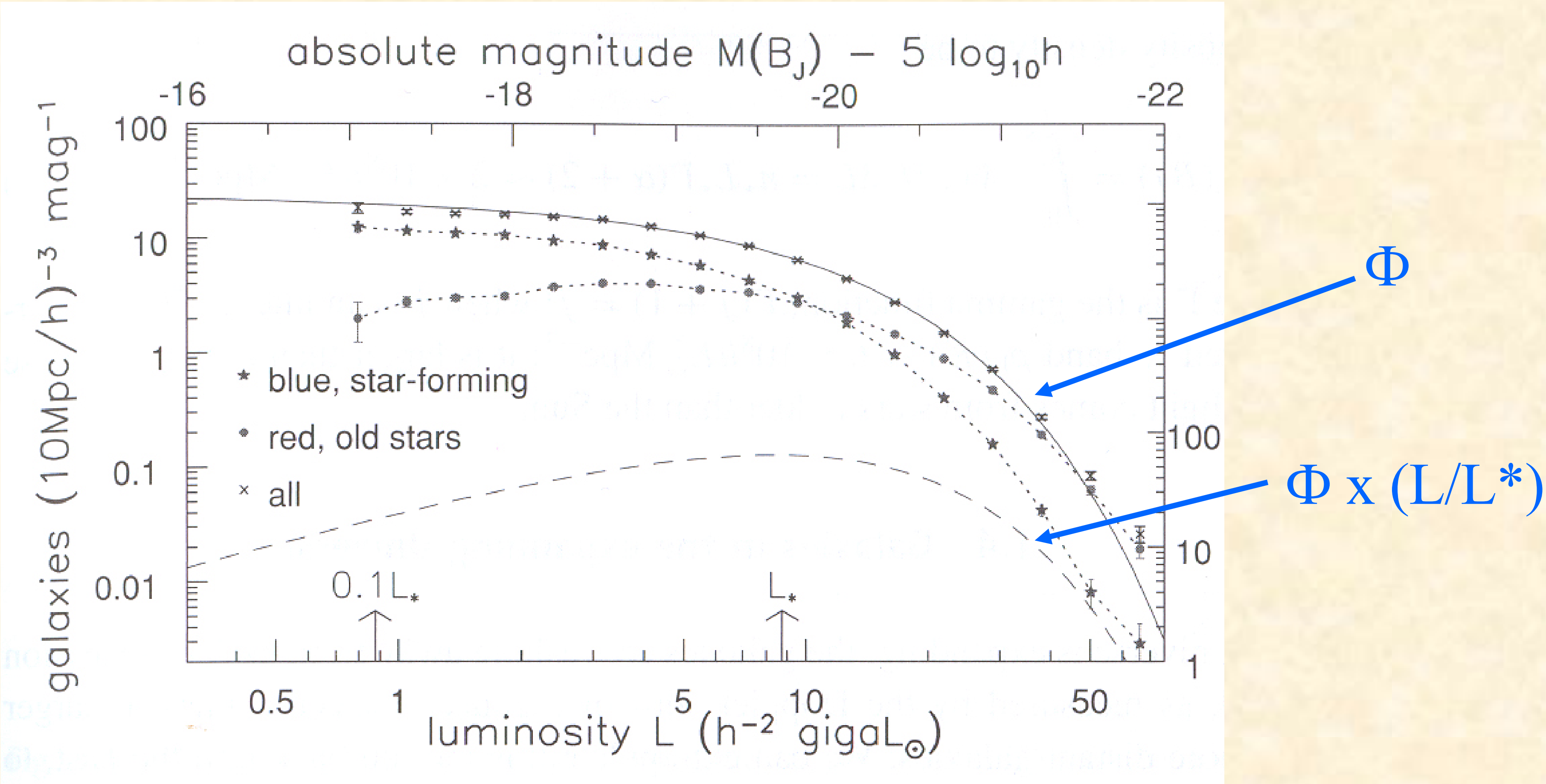
Galaxy Luminosity Functions

- Φ (L) dL – # of galaxies with luminosities between L and L + dL (or M and M + dM) per Mpc^3
- Need to correct for Malmquist bias: can only count galaxies to a limiting magnitude (miss distant, faint galaxies)
- Φ often described by the Schechter Luminosity Function:

$$\Phi(L) = \frac{n*}{L*}\left(\frac{L}{L*}\right)^{\alpha} \exp\left(\frac{-L}{L*}\right)$$

- n* = normalization constant ≈ 0.02 h^3 Mpc^{-3}
 (where h = H_0/100 km s^{-1} Mpc^{-1} = 0.73)
- L* = turnover luminosity at the high end ≈ 9 x 10^9 h^{-2} $L_\odot$
- α = slope at low-luminosity end ≈ – 0.4

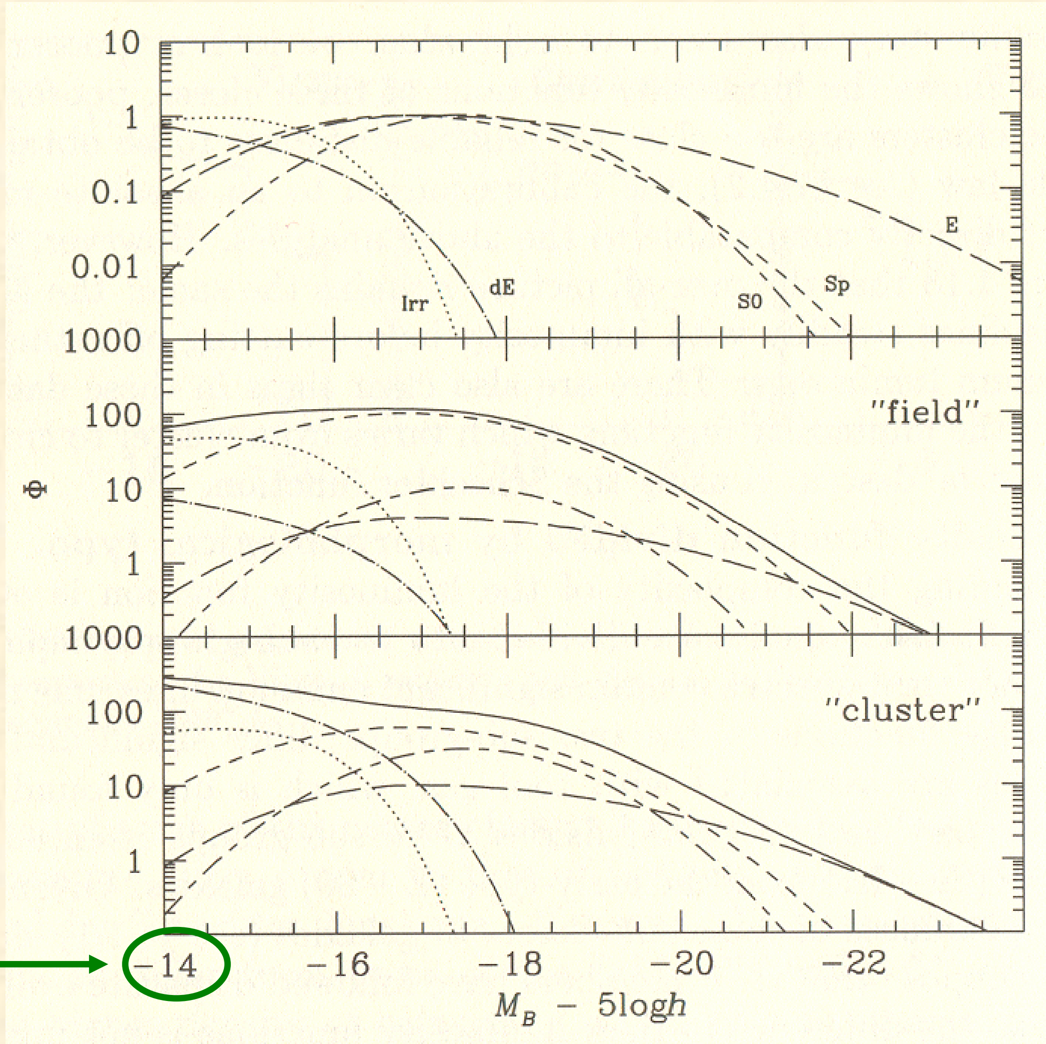
Luminosity Function - Data



(2dF Survey - Sparke & Gallagher, p. 45)

- Giant E's dominate at high end
- Most of the luminosity comes from bright galaxies

Luminosity Functions by Morphological Type



Is this it?

arbitrary normalization

correct relative normalization

(Binney & Merrifield p. 168)

- dE's and Irr's dominate at low luminosities
- Brightest galaxies are giant E's and cD's in centers of clusters
- Spirals are less common in clusters (and their numbers increase with distance from center)

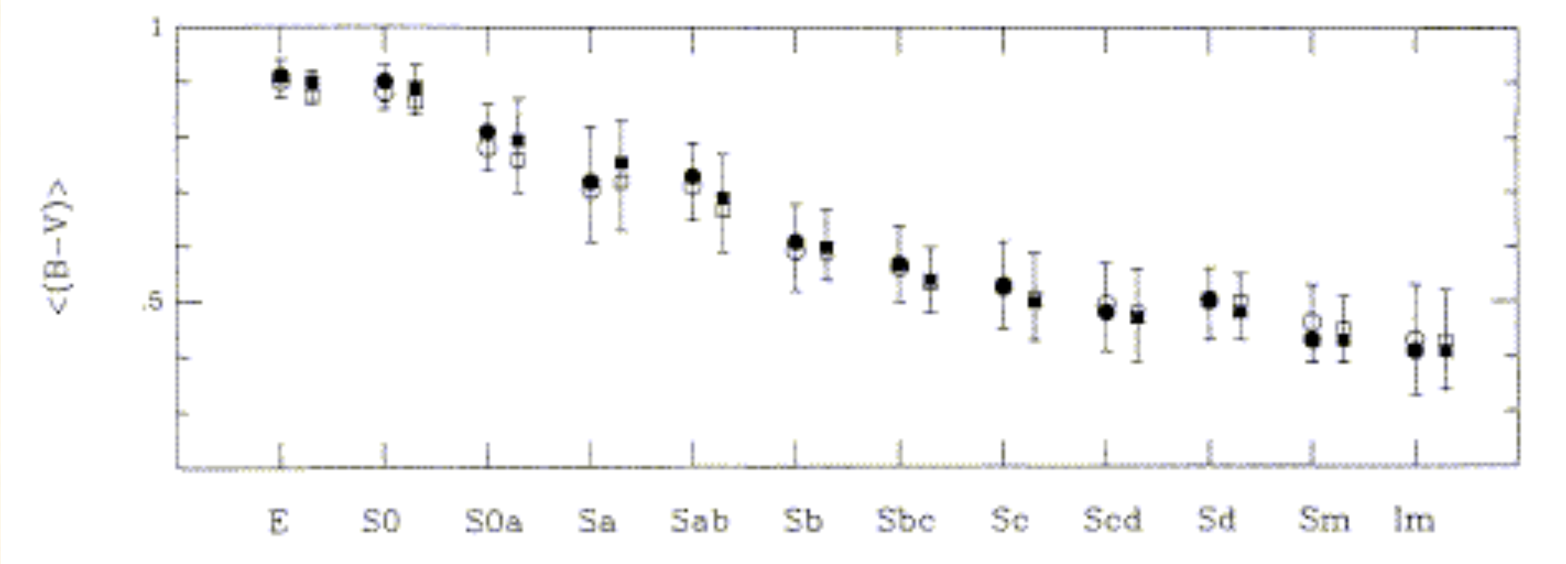
Local Group

Name	Alternate Name	Coordinates RA (1950)	Dec	Type	Distance (kpc)	M_V
M31	NGC 224	00 40.0	+40 59	Sb	725	−21.1
Milky Way	Galaxy	17 42.4	−28 55	Sbc	8	−20.6
M33	NGC 598	01 31.1	+30 24	Sc	795	−18.9
LMC		05 24.0	−69 48	Irr	49	−18.1
IC 10		00 17.7	+59 01	Irr	1250	−17.6
NGC 6822	DDO 209	19 42.1	−14 56	Irr	540	−16.4
M32	NGC 221	00 40.0	+40 36	dE2	725	−16.4
NGC 205		00 37.6	+41 25	dE5	725	−16.3
SMC		00 51.0	−73 06	Irr	58	−16.2
NGC 3109	DDO 236	10 00.8	−25 55	Irr	1260	−15.8
NGC 185		00 36.2	+48 04	dE3	620	−15.3
IC 1613	DDO 8	01 02.2	+01 51	Irr	765	−14.9
NGC 147	DDO 3	00 30.5	+48 14	dE4	589	−14.8
Sextans A	DDO 75	10 08.6	−04 28	Irr	1450	−14.4
Sextans B	DDO 70	09 57.4	+05 34	Irr	1300	−14.3
WLM	DDO 221	23 59.4	−15 45	Irr	940	−14.0
Sagittarius		18 51.9	−30 30	dSph/E7	24	−14.0
Fornax		02 37.8	−34 44	dSph/E3	131	−13.0
Pegasus	DDO 216	23 26.1	+14 28	Irr	759	−12.7
Leo I	DDO 74	10 05.8	+12 33	dSph/E3	270	−12.0
Leo A	DDO 69	09 56.5	+30 59	Irr	692	−11.7
And II		01 13.5	+33 09	dSph/E3	587	−11.7
And I		00 43.0	+37 44	dSph/E0	790	−11.7
SagDIG		19 27.9	−17 47	Irr	1150	−11.0
Antlia		10 01.8	−27 05	dSph/E3	1150	−10.7
Sculptor		00 57.6	−33 58	dSph/E3	78	−10.7
And III		00 32.6	+36 12	dSph/E6	790	−10.2
Leo II	DDO 93	11 10.8	+22 26	dSph/E0	230	−10.2
Sextans		10 10.6	−01 24	dSph/E4	90	−10.0
Phoenix		01 49.0	−44 42	Irr	390	− 9.9
LGS 3		01 01.2	+21 37	Irr	760	− 9.7
Tucana		22 38.5	−64 41	dSph/E5	900	− 9.6
Carina		06 40.4	−50 55	dSph/E4	87	− 9.2
Ursa Minor	DDO 199	15 08.2	+67 23	dSph/E5	69	− 8.9
Draco	DDO 208	17 19.2	+57 58	dSph/E3	76	− 8.6

(Binney & Merrifield p. 168)

- Many galaxies with low luminosities and low surface brightnesses
- A 3D view can be found at http://www.atlasoftheuniverse.com/localgr.html

Global Correlations: Color vs. Type



(Roberts and Haynes, 1994 ARA&A 32, 115)

Trends:

Ellipticals → bulges → disks

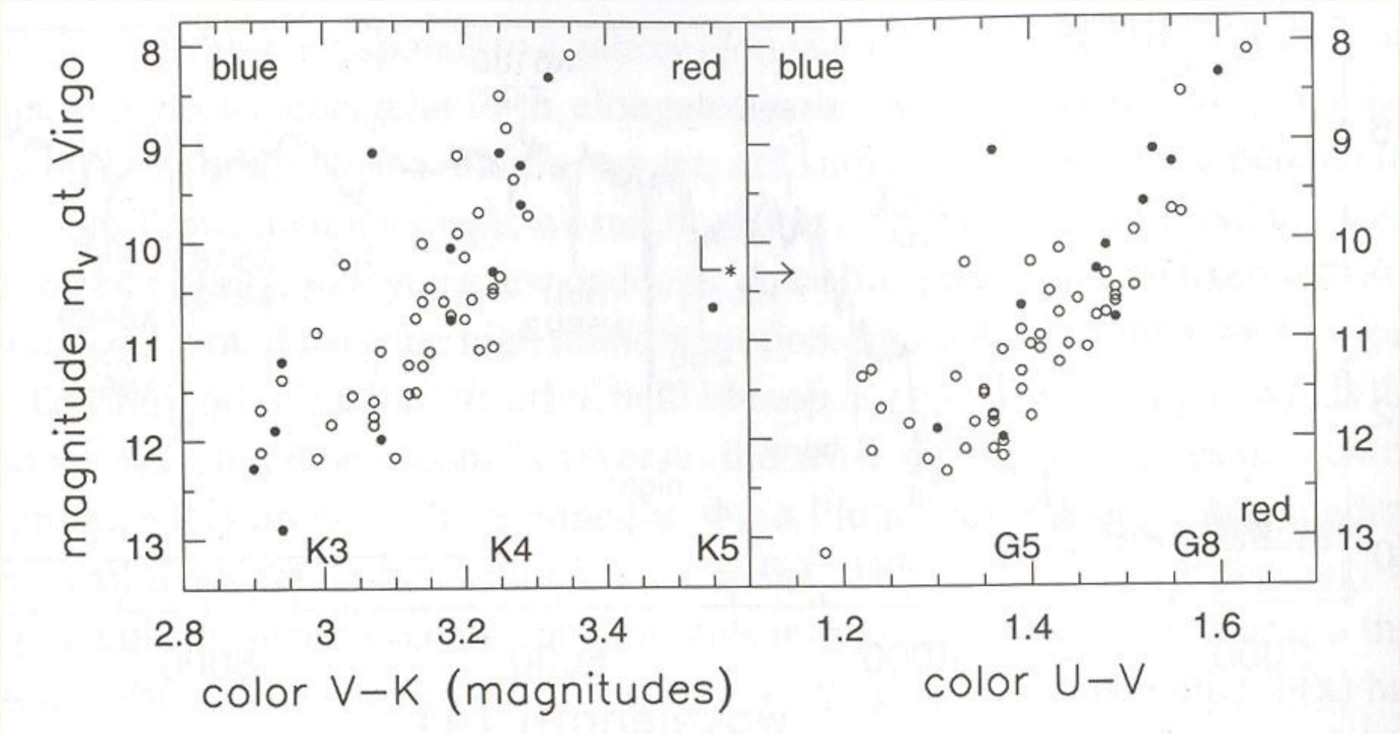
red → blue

old average population → young

low metallicity → high

- Oversimplification; e.g., metallicity in the Galactic bulge decreases with radius (from above solar to below)
- Difficult to separate effects of stellar populations, metallicity, and dust → use spectroscopy

Ellipticals: Color vs. Luminosity

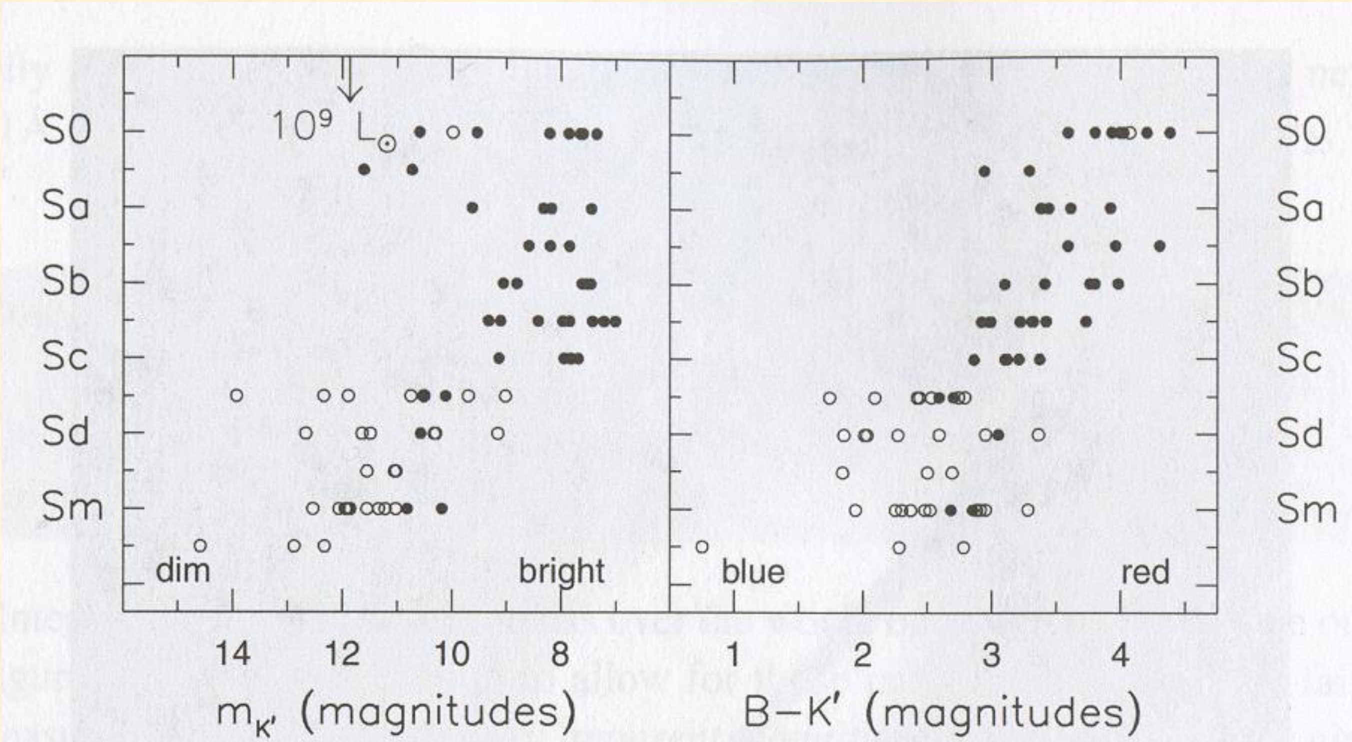


(Sparke & Gallagher, p. 269)

- Brighter ellipticals are redder

→ higher metallicities, rather than older stellar populations (confirmed from spectra of Fe, Mg absorption lines)

Global Correlations (Spirals)



(Galaxies in Ursa Major Group; Sparke & Gallagher, p. 201)

- Earlier types have 1) higher luminosities, 2) higher I_R, 3) redder colors, 4) lower H I mass, 5) less star formation, and 6) fewer H II regions
  - Due in part to prominence of bulge. (1, 2, 3)
  - Also, less gas available for star formation in the disk at present epoch (3, 4, 5, 6)