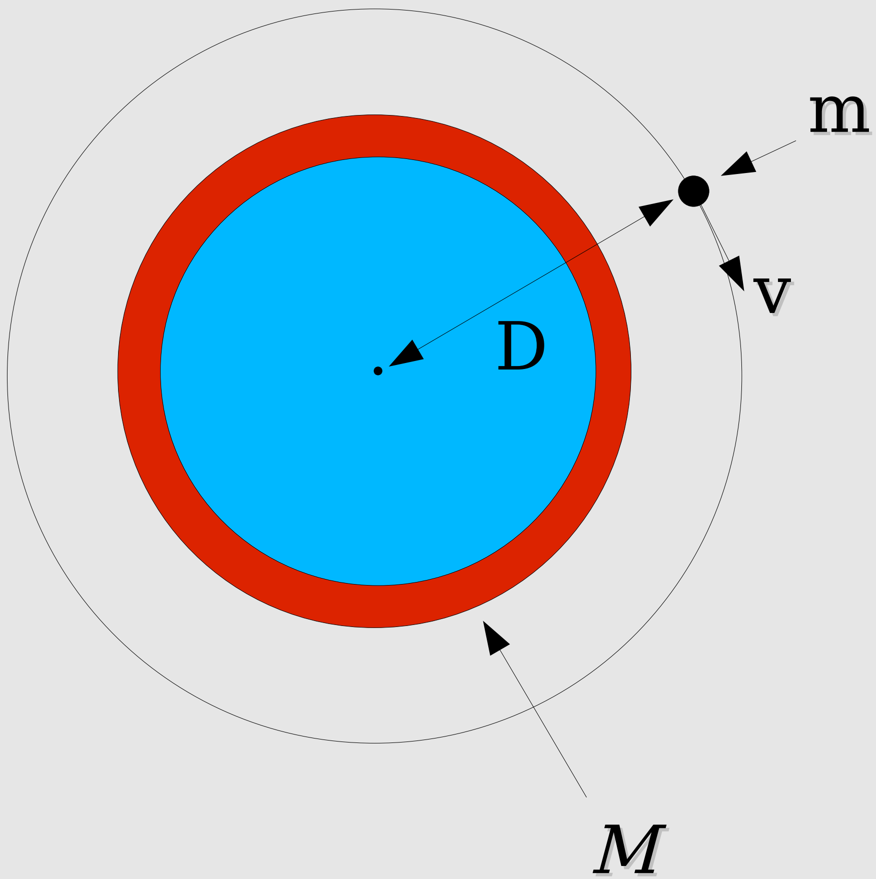
Tidal Interactions

Tidal Stripping



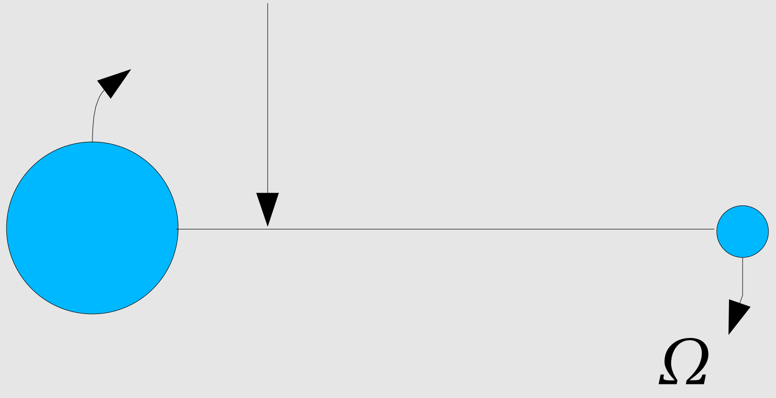
If the mass m is close enough to the particles in M then the particles closest to M are at risk of being removed or stripped from the larger body.

Tidal Stripping cont.

If we select a frame of reference that rotates at the same rate as the satellite m (Ω=v/(2πD)). We do this so that we have a stationary problem.

Lets also look at this in Center of Mass coordinates.

$$x_{CM} = \frac{D\,M}{M+m}$$



We can write the effective potential in the form

$$\Phi_{eff}(x) = -\frac{GM}{|D-x|} - \frac{Gm}{|x|} - \frac{\Omega^2}{2}\left(x - \frac{DM}{M+m}\right)^2$$

Normal gravitational force and angular momentum

This potential will have 3 maxima and we can find these by

$$\frac{\partial \Phi_{eff}}{\partial x} = -\frac{GM}{(D-x)^2} \pm \frac{Gm}{x^2} - \Omega^2\left(x - \frac{DM}{M+m}\right) = 0$$

But remember for a circular orbit

$$V^2 = \frac{GM}{r} \quad \text{and the acceleration is} \quad a = \frac{V^2}{r} = \frac{GM}{r^2}$$

Since Ω=v/(2πr) then $$a = \frac{V^2}{r} = \Omega^2 r$$

But since we are in the CM coordinate system

$$a = \Omega^2 r = \Omega^2 \frac{DM}{(M+m)} = \frac{GM}{D^2}$$

Solving this for Ω^2

$$\Omega^2 = \frac{G(M+m)}{D^3}$$

Substituting this for Ω^2 below

$$\frac{\partial \Phi_{eff}}{\partial x} = -\frac{GM}{(D-x)^2} \pm \frac{Gm}{x^2} - \Omega^2 \left(x - \frac{DM}{M+m}\right) = 0$$

We get

$$-\frac{GM}{(D-x)^2} \pm \frac{Gm}{x^2} - \frac{G(M+m)}{D^3}\left(x - \frac{DM}{M+m}\right) = 0$$

If m<<M then x <<D we can rewrite our equation as

$$\frac{G\,M}{D\left(1-\frac{x}{D}\right)^{2}} \pm \frac{G\,m}{x^{2}} - \frac{GM}{D^{2}} + \frac{M+m}{D^{3}} = 0$$

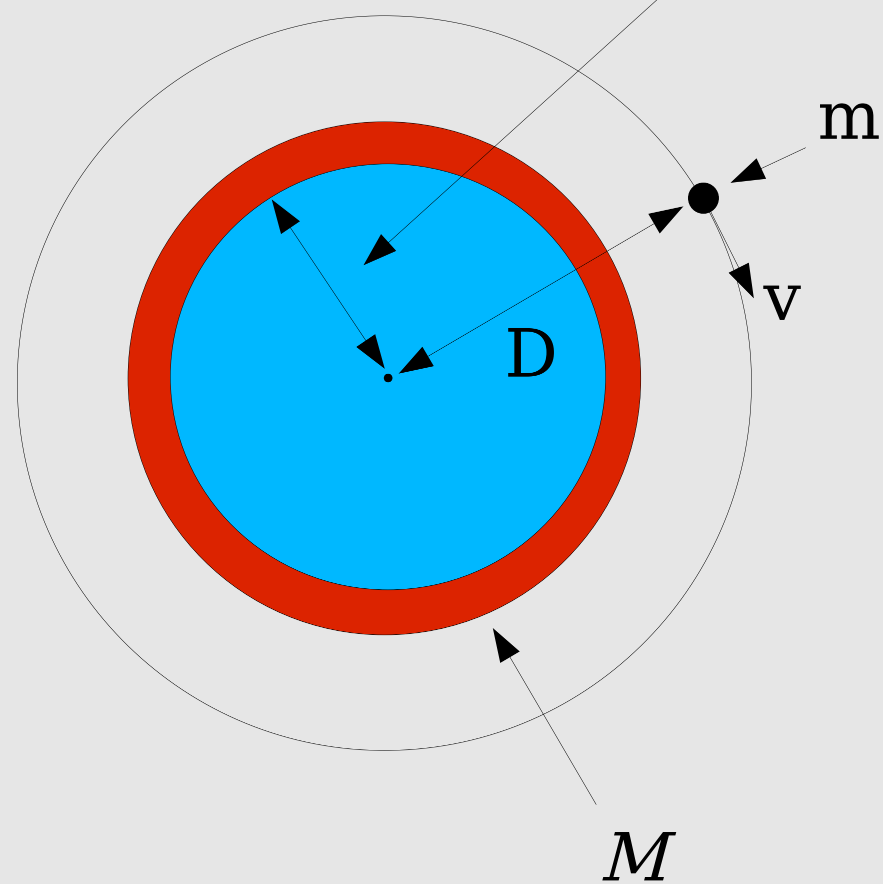
Expanding $(1 + x/D)^{-2}$ in a Taylor series

$$\frac{G\,M}{D^{2}}\left(1+\frac{2\,\mathrm{x}}{D}+\ldots\right) \mp \frac{G\,m}{x^{2}} - \frac{GM}{D^{2}} + \frac{M+m}{D^{3}} = 0$$

Solving for x we get

$$x = \pm D\left[\frac{m}{M\left(3+m/M\right)}\right]^{\frac{1}{3}} \approx \pm\left(\frac{m}{3\mathrm{M}}\right)^{\frac{1}{3}} D$$

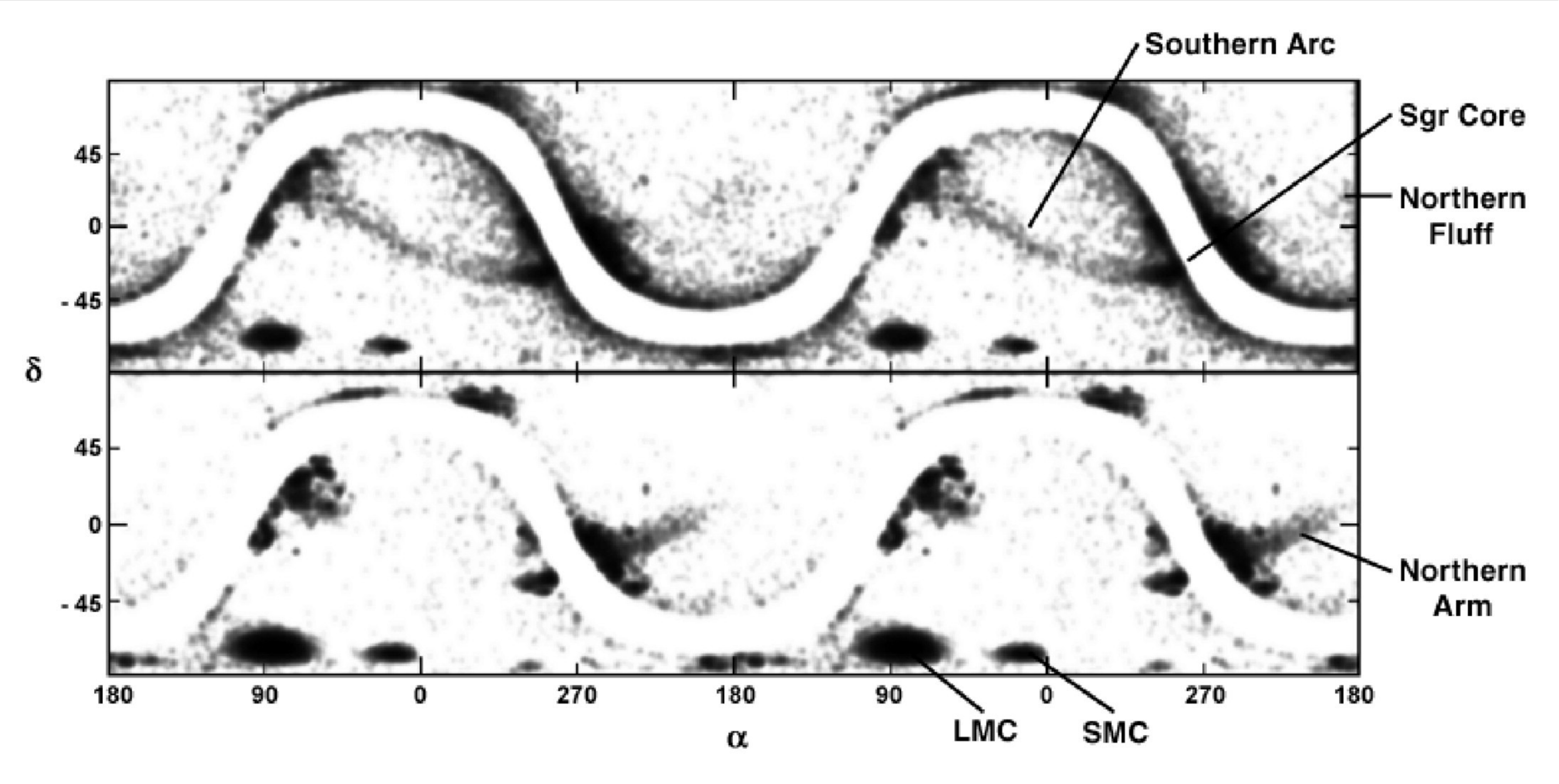
x is called the Jacobi limit or the Roche limit and is written as r_J

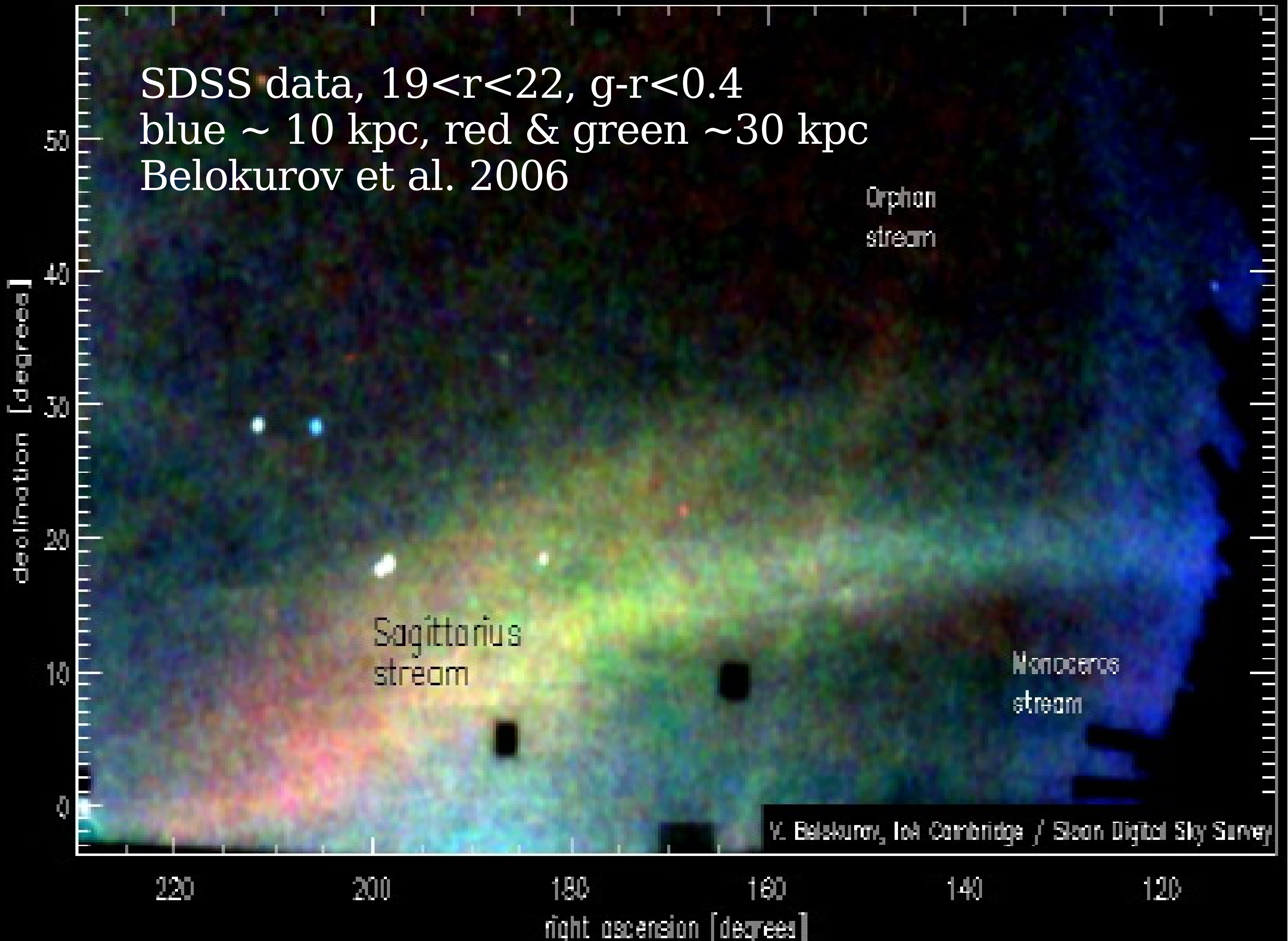


- This provides a crude estimate of the true tidal radius
  - In general the system will not have a circular orbit
  - We derived this for point masses and most systems are extended
  - If done in 3-d (so we get a surface) this is not a spherical surface
  - If $r_J > x$ a particle will not necessarily escape. Numerical studies show that there are some stable orbits up to $r = 2r_J$.

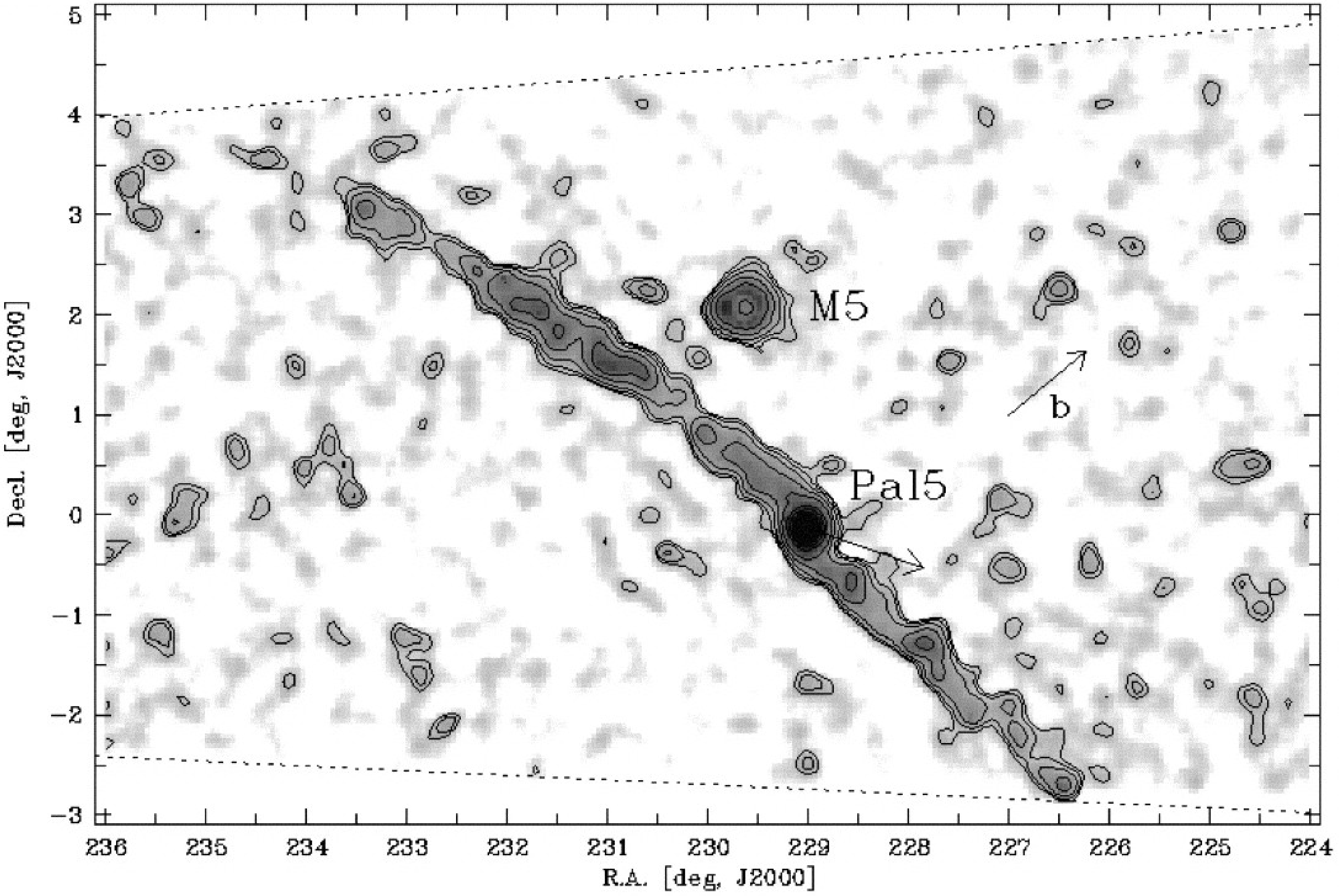

Sgr dSph as know in 1996
Wise, Gillmore, Franx 1997

Studies using the 2MASS survey showed that tidal streams from the Sgr dwarf galaxy all around the sky (Majewski 2003)




SDSS data, 19<r<22, g-r<0.4
blue ~ 10 kpc, red & green ~30 kpc
Belokurov et al. 2006
Orphan
stream
Sagittarius
stream
Monoceros
stream
V. Belokurov, IoA Cambridge / Sloan Digital Sky Survey
declination [degrees]
right ascension [degrees]
0
10
20
30
40
50
220
200
180
160
140
120

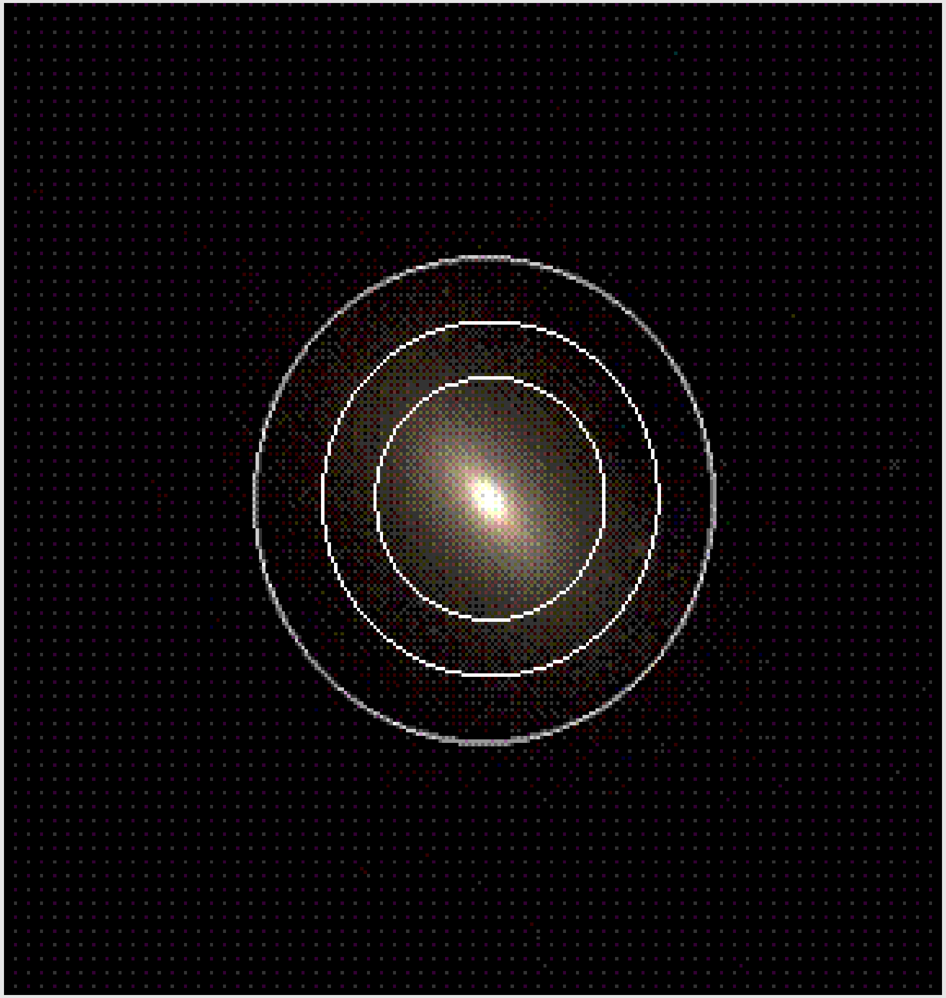
ODENKIRCHEN et al. 2003



Dust and Gas in External Galaxies

Galaxy Photometry

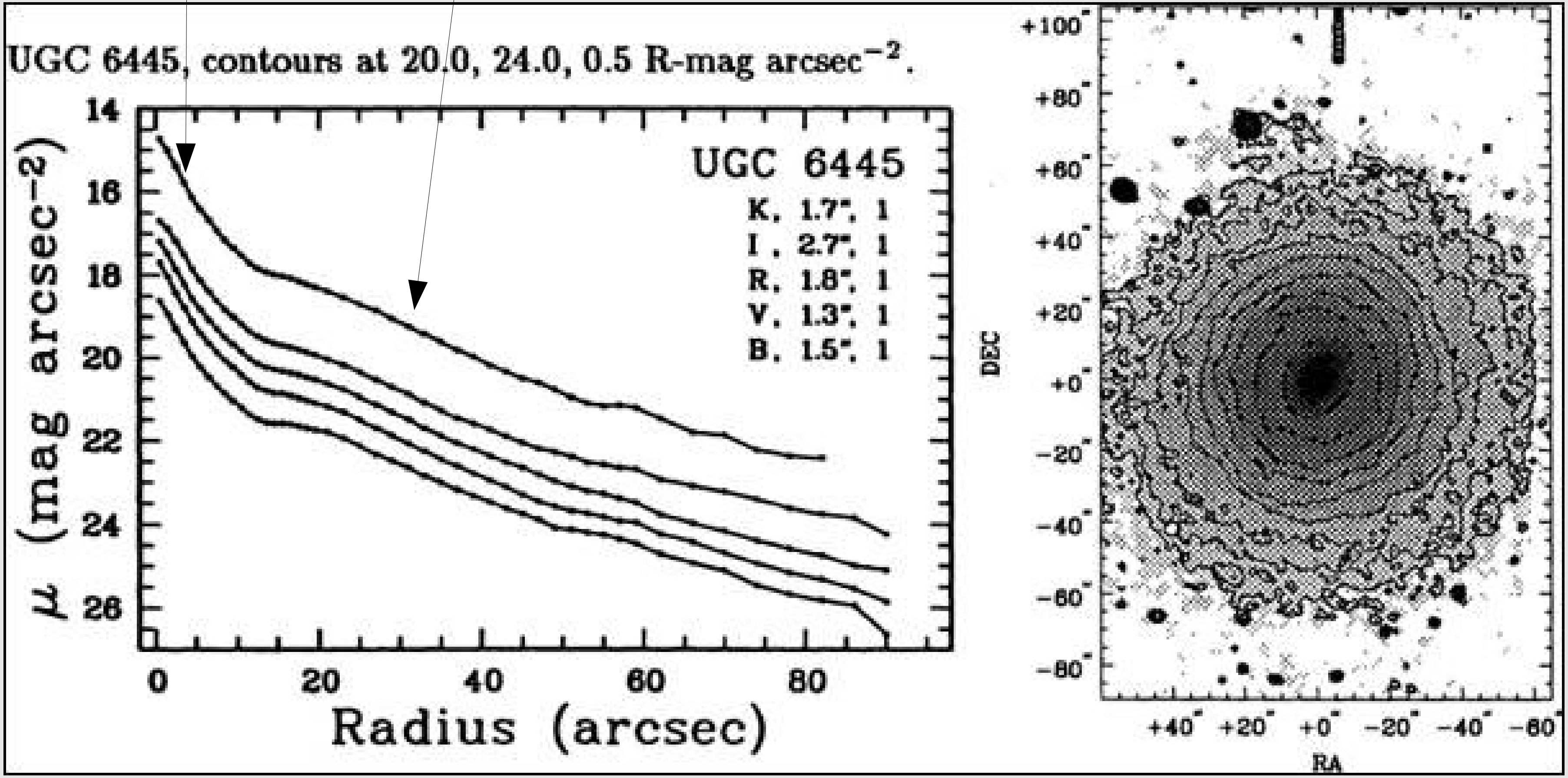
- Surface Photometry is often used to measure stellar distribution
- Measured in concentric radii (mag/sq arcsec)
- Use a fit function to measure SB
- Compare different anulii e.g. Concentration index, asymmetry



Spiral galaxy profiles

Two components

Bulge Disk



Elliptical galaxy profiles

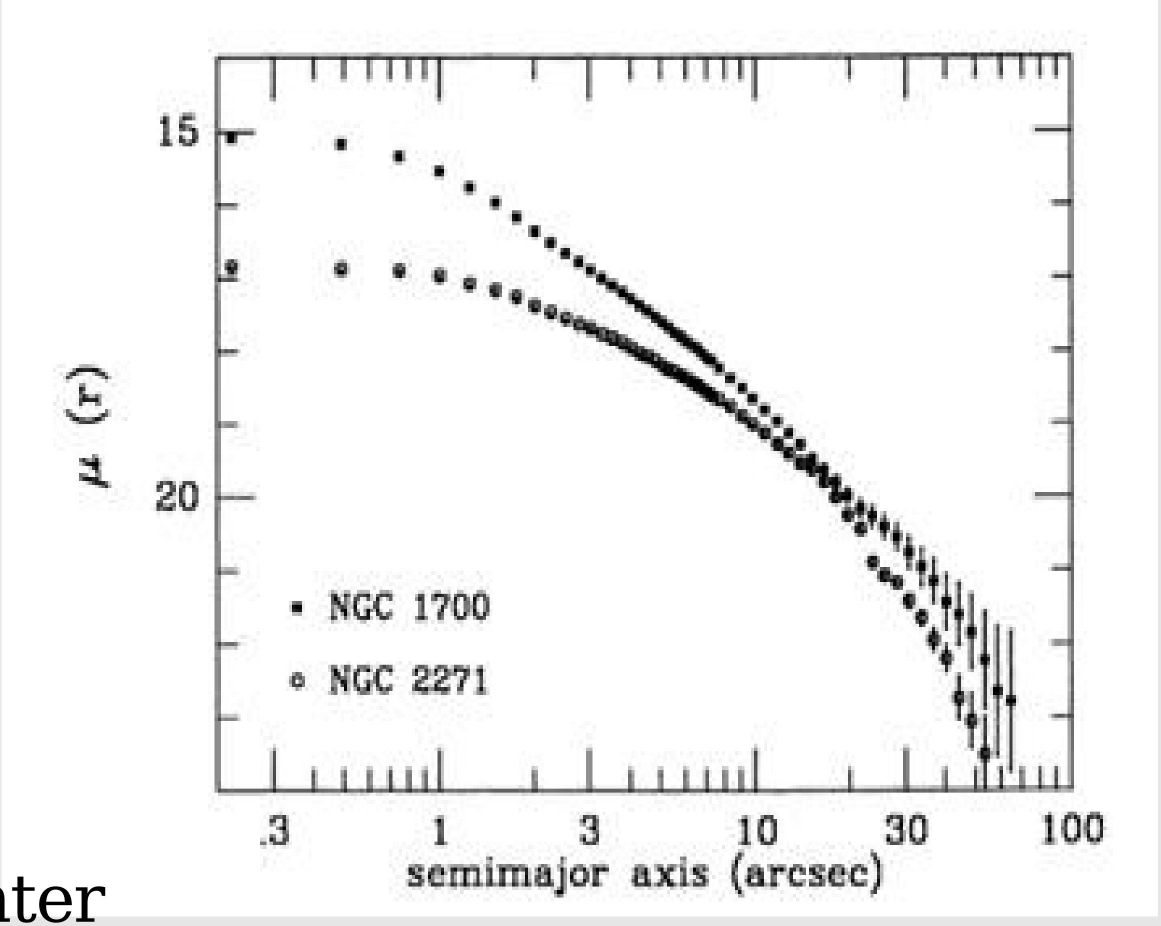
Often well fit with an exponential profile

$$I(r) = I(r_e) \exp\left[-b\left(\left(\frac{r}{r_e}\right)^{\frac{1}{n}} - 1\right)\right]$$

If n = 4 this is a de Vaucouleur's law for general n Sersic's law.

Often flattens in the center

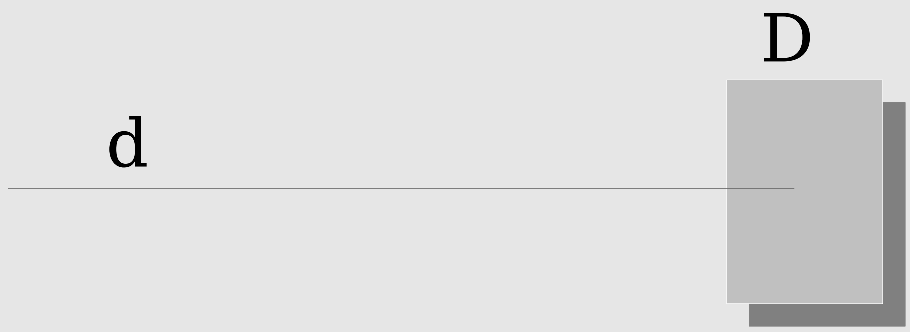
Fit spiral bulges as well



Measuring Galaxy Luminosities

Galaxy luminosities are much harder to measure than stellar luminosities because they are extended objects and have no well defined edges

We define the surface brightness of a galaxy to as the amount of light per square arcsecond on the sky.



If we have a square patch with side length D, in a galaxy at a distance d from us we see that this subtends an angle $\alpha = D/d$ on the sky.

If we look at the luminosity of all the stars in this small patch L, then the total flux we see is

$$F = \frac{L}{4\pi d^2}$$

And we can define surface brightness as

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

The units for surface brightness is mag arcsec^{-2}. So if a galaxy has a surface brightness of 20 mag arcsec^{-2} then we receive as many photons from one square arcsecond of the galaxy that we would observing a 20 magnitude star.

Typical surface brightness values for galaxies are about 18 mag arcsec^{-2} in the center.

To find the total brightness of a galaxy we need to integrate the light coming from all parts of the system. Since galaxies do not have sharp edges we typically measure the brightness out to some brightness called the limiting isophote.

Measurements are typically integrated out to some limiting isophote and is called the isophotal magnitude. A typical limit is 25 mag arcsec^{-2}. This is usually measured in the B band ($\lambda_{\text{Central}} = 4400$Å.)

Properties of Bulges

Bulges are some of the densest stellar systems. They can be flattened, ellipsoidal or bar-like. The surface brightness of a bulge is often approximated by the Sersic law:

$$I(R) = I(0) \exp\{-(R/R_0)^{1/n}\}$$

Recall that n=1 corresponds to an exponential decline, and n=4 is the de Vaucouleurs law.

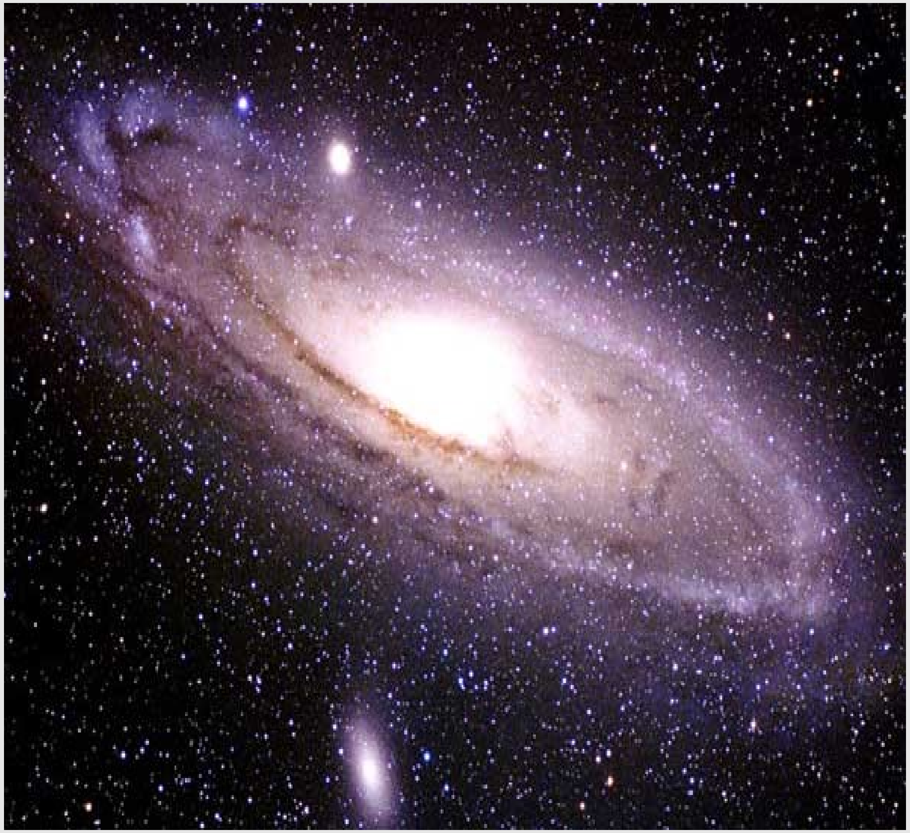
About half of all disk galaxies contain a central bar-like structure. The long to short axis ratio can be as large as 5:1.

When viewed edge-on, the presence of a bar can be noticed from the boxy shape of the halo. In some cases the isophotes are squashed, and the bulge/bar has a peanut-like shape.

Colors of Disk Galaxies

M31 is the closest spiral galaxy (besides the MW)

- At r< 6 kpc the bulge dominates the light and the color is similar to an E galaxy
- Further out the young stars contribute more and more to the light



Population I & II

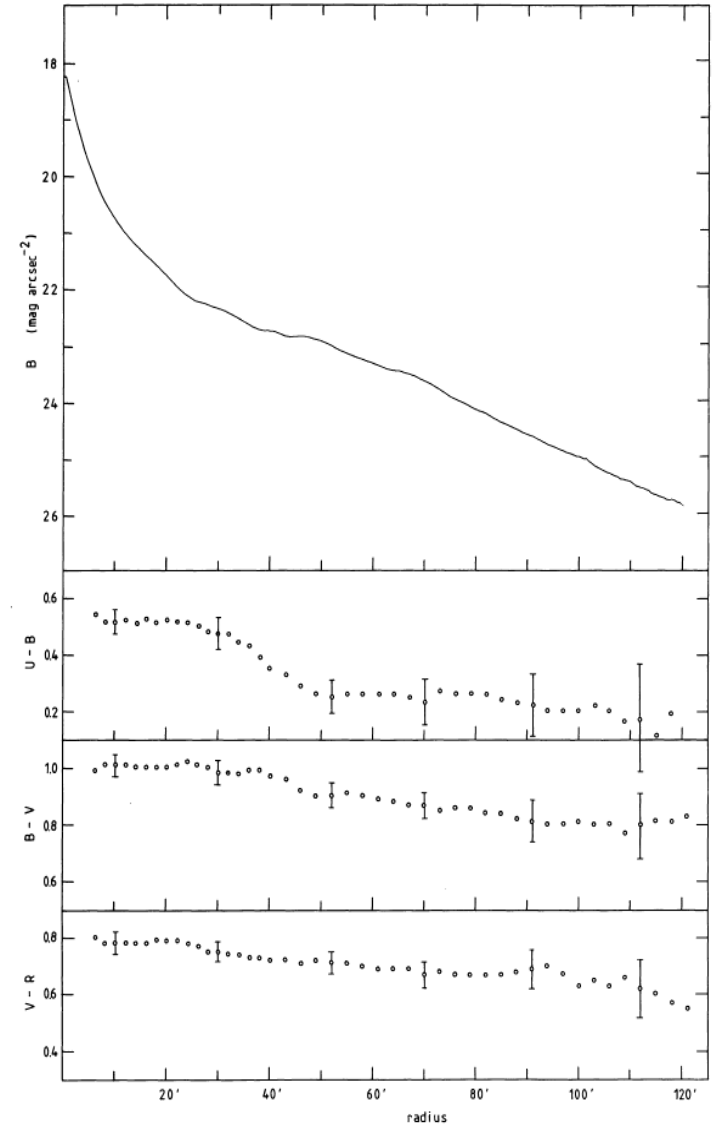


FIGURE 12. — The global light and color profiles of M31 obtained from the data by averaging the intensity distributions in ellipses centred on the nucleus of the galaxy. Foreground stars were removed from the data beforehand. The uncertainties were estimated from comparisons of the global profiles derived from different plates in the same color band.

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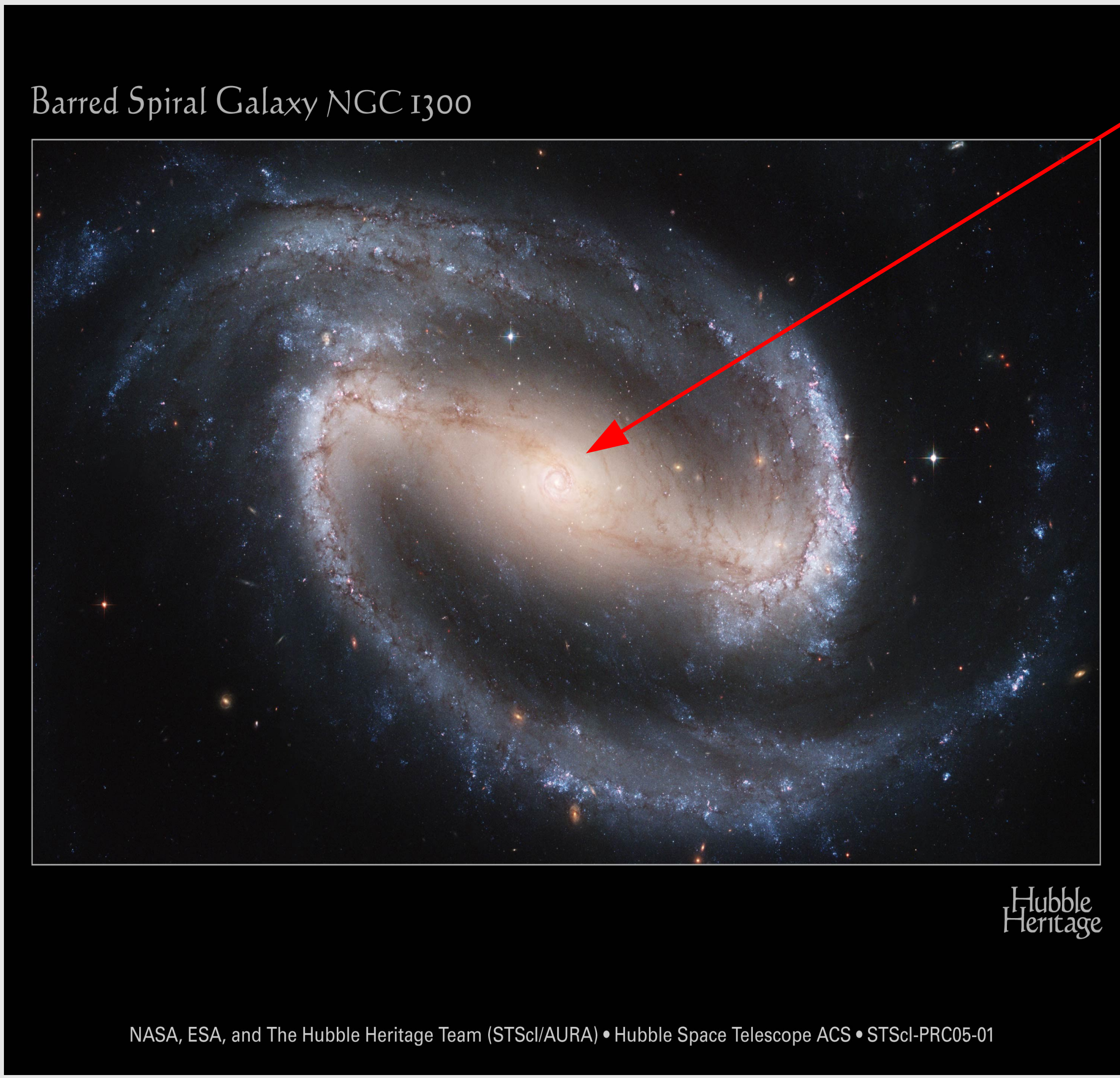
Stellar Populations I & II

- Population I
  - Young
  - Metal rich
  - Found in galaxy disks
  - Closely associated with spiral arms
    - Luminous hot young stars (O & B stars)
    - Cepheid variables
    - Dust Lanes
    - HII regions
    - Metal rich open clusters

Stellar Populations I & II



- Population II
  - Old
  - Metal poor
  - Found in Globular clusters, Spiral bulges and Ellipticals
    - Red giants
    - RR Lyrae stars
    - Long period variables (Mira)
    - Semi-regular variables α-Herc

But remember there are several effects that can complicate the picture

1) Metallicity – metal poor stars are bluer than metal rich stars

2) Age – younger stars are generally bluer

3) Dust – makes stars appear redder

Spirals are Complex

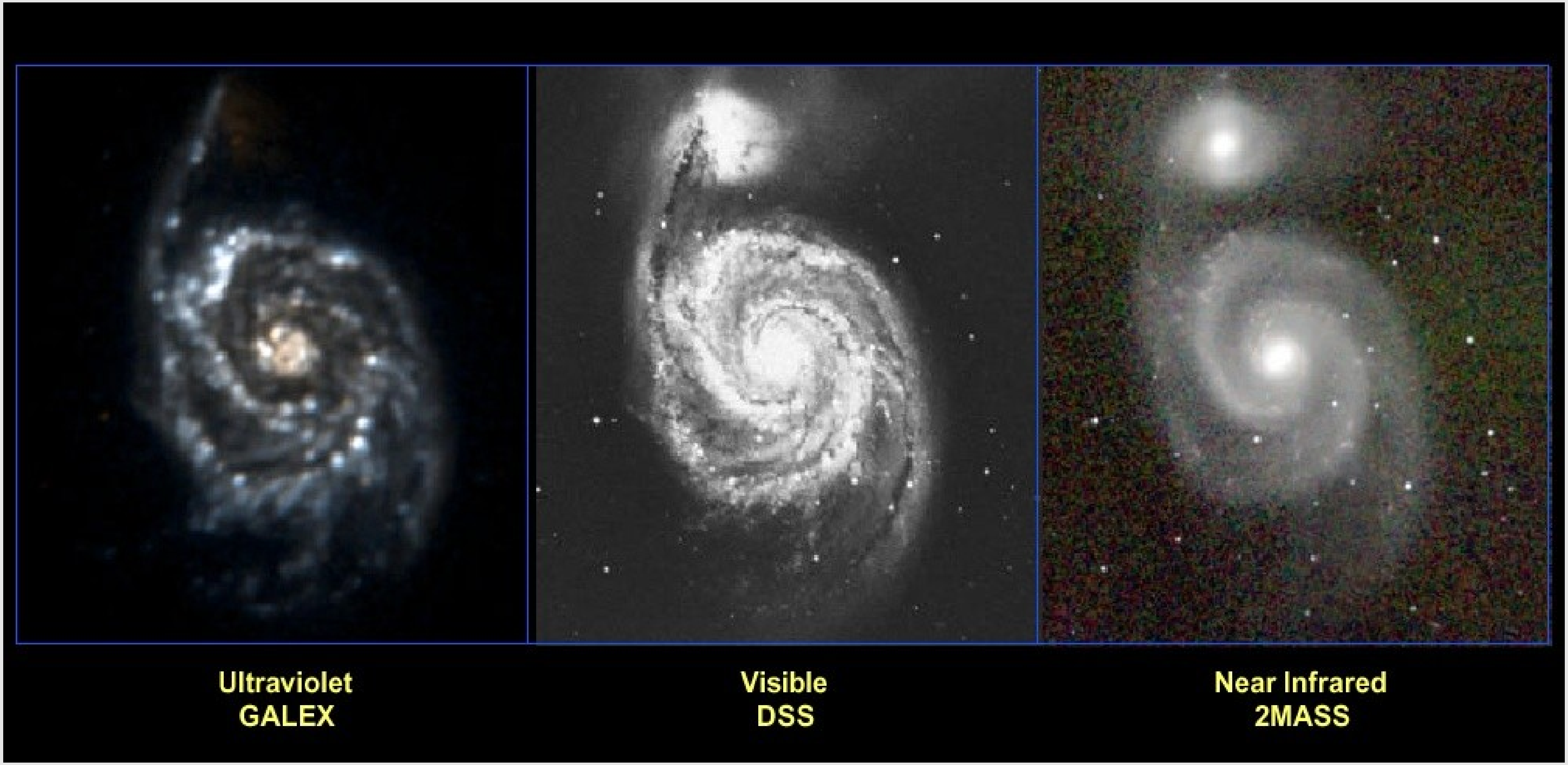
- As we've seen spirals are complex systems
  - Wide range of morphologies
  - Many fine scale details
    - HII regions
    - Structure in the arms
    - bulge/disk ratio has a large range
  - Wide range of stellar populations
    - Young
    - Old
    - Intermediate

- Wide range of stellar dynamics
  - “Cold” disk stars – young rotationally supported
  - “Hot” halo stars – supported by velocity dispersion, includes the bulge stars
- Has a substantial ISM
  - HI (atomic gas)
  - H_2 (molecular gas)
  - HII (ionized Hydrogen)

Spiral Building Blocks

- Basic Components
  - Disk, metal rich stars, ISM is metal rich, stars have orbits that are nearly circular, small random velocities in the z direction, spiral patterns
  - Bulge, old metal poor stars, high densities, and motions are mostly random, like ellipticals
  - Bars, seen in also 50% of all spirals, long lived features
  - Nucleus, very high stellar densities, often has a supermassive black hole
  - Halo, very diffuse, low density, metal poor old stars, GC's, Hot (10^6 K) gas very little of the total light contributing only few percent
  - Dark Matter, most of the mass, composition ?

M81 seen in different bandpasses



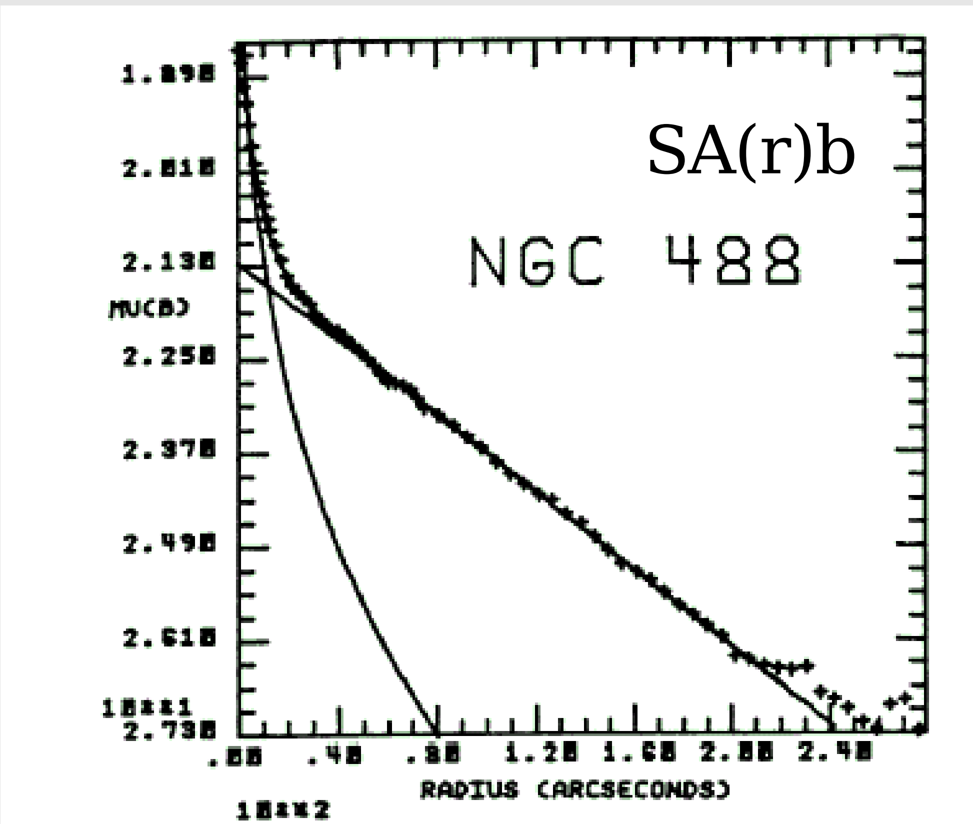
Spiral galaxy profiles

- Luminosity
  - Disk follows an exponential model

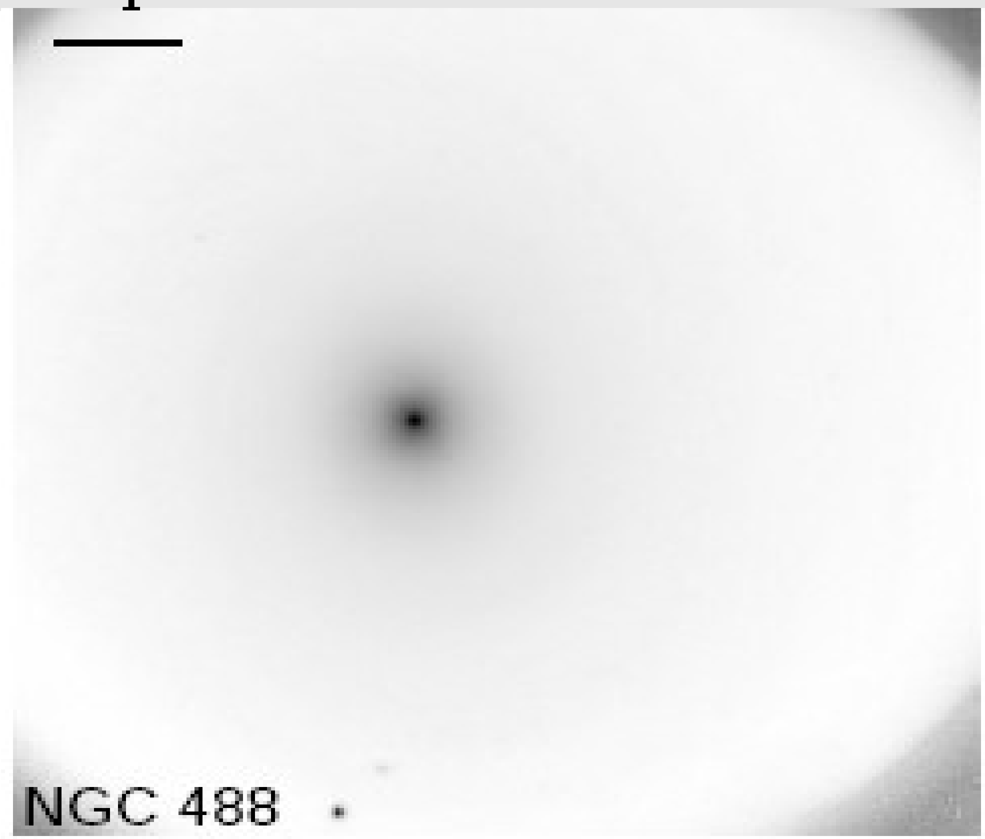
    $$\Sigma(r) = \Sigma(0)\, e^{-r/r_d}$$
  - The disk scale length (r_d) is typically 2-6 kpc
  - Disk fades dramatically after 4-5 r_d
  - Bulge follows $r^{1/4}$ law (like many Ellipticals)

Decomposition of spiral profiles

We can fit the 1-D profiles with a bulge + disk model and compute the bulge to disk ratio.



2 kpc



Boroson 1981

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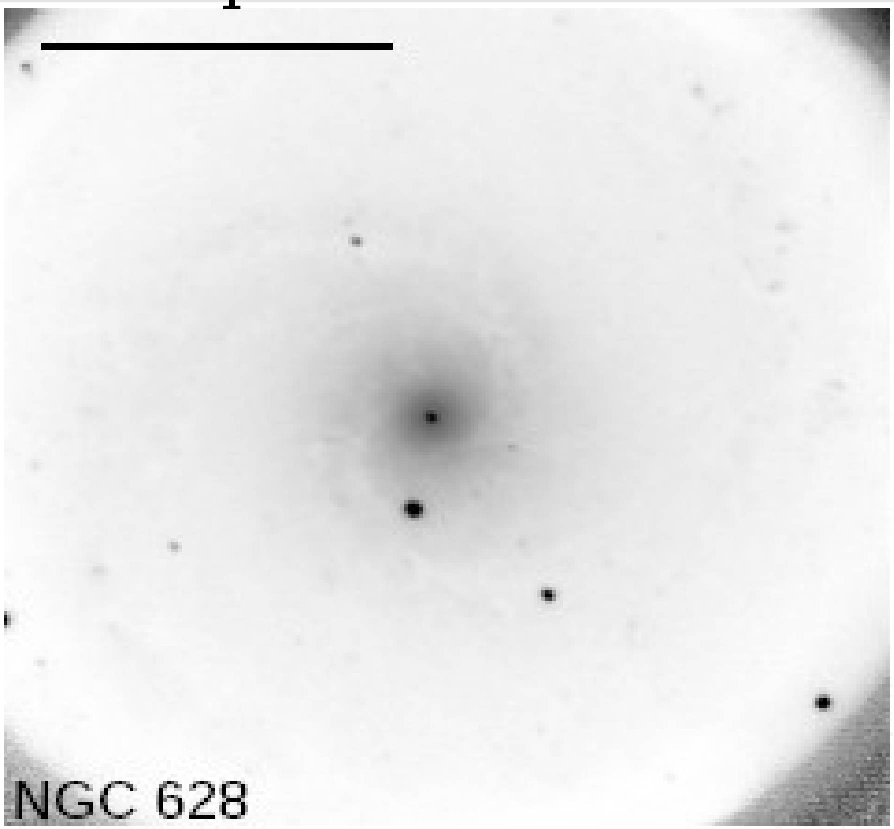
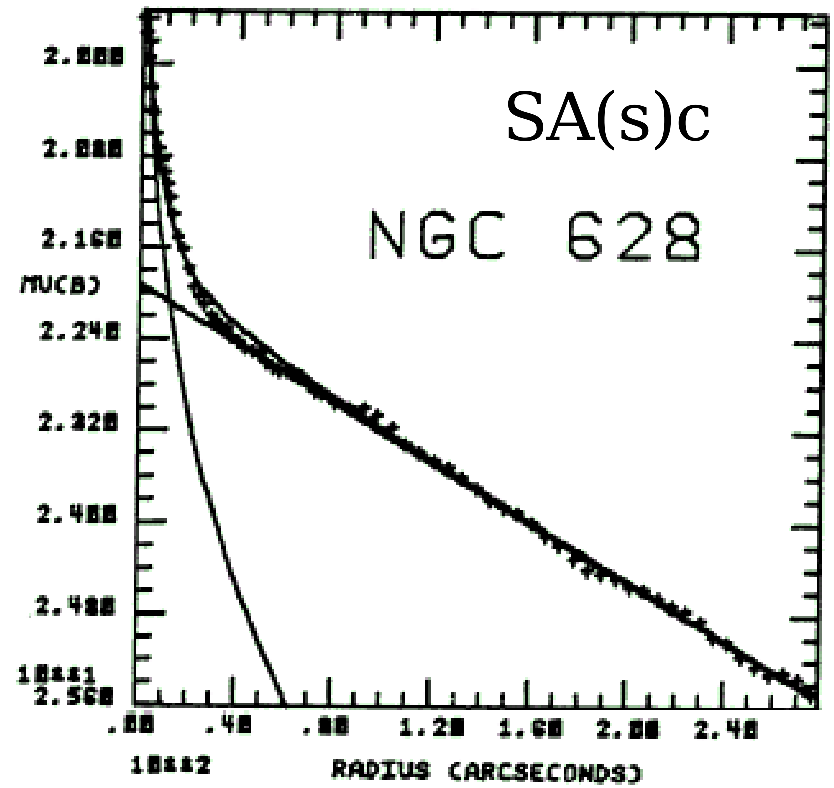
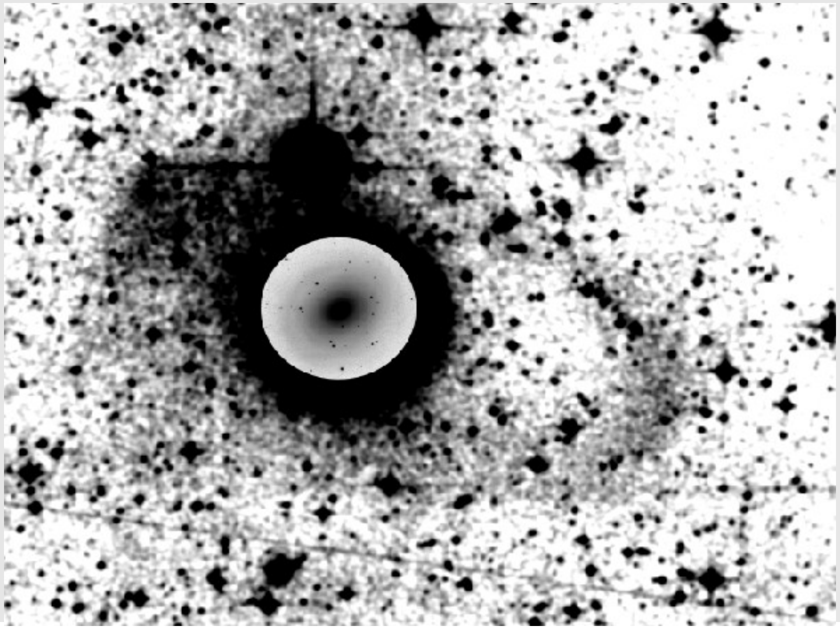
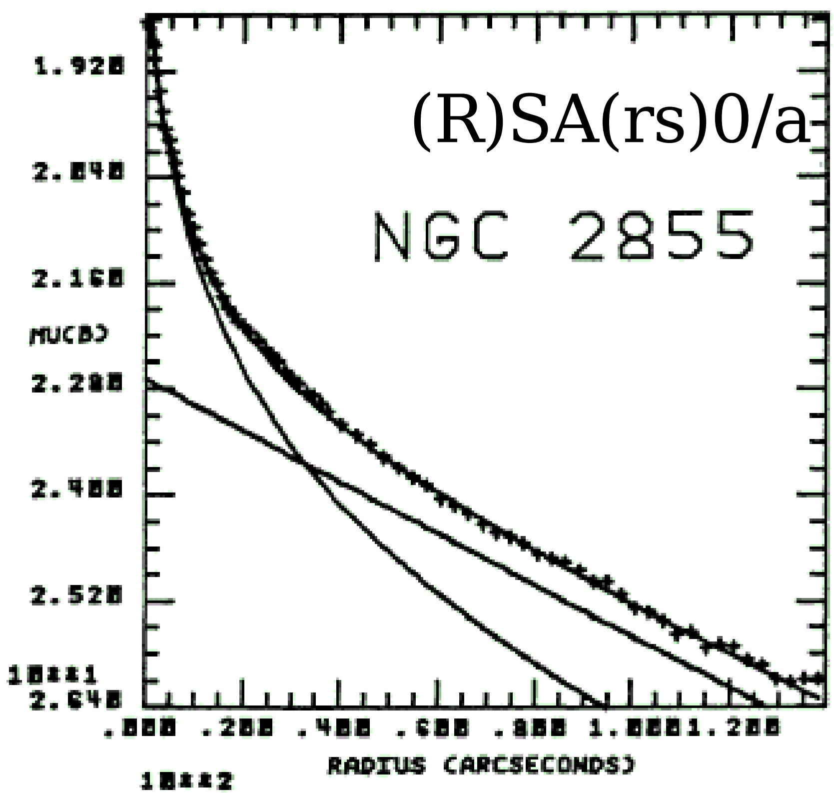
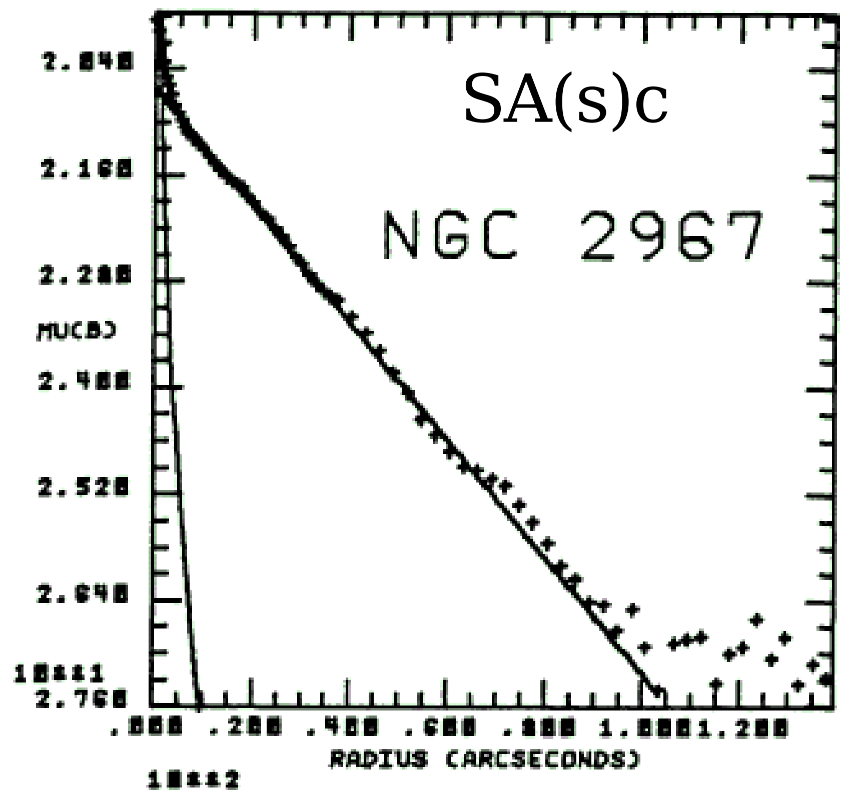




Boroson 1981







Boroson 1981

Freeman's Law

Freeman's law states that the central surface brightness of a spiral galaxy is about 21.7 mag arcsec^{2}.

Yoshizawa and Wakamatsu (1975)
(24 galaxies) 21.28+/- 0.71
Schweiezer (1976) (6 galaxies)
21.67+/- 0.35

Disney (1976) showed that this is an observational effect and led to the search for LSB galaxies.

Boroson (1981) also showed that there is a fairly large range of central SB.

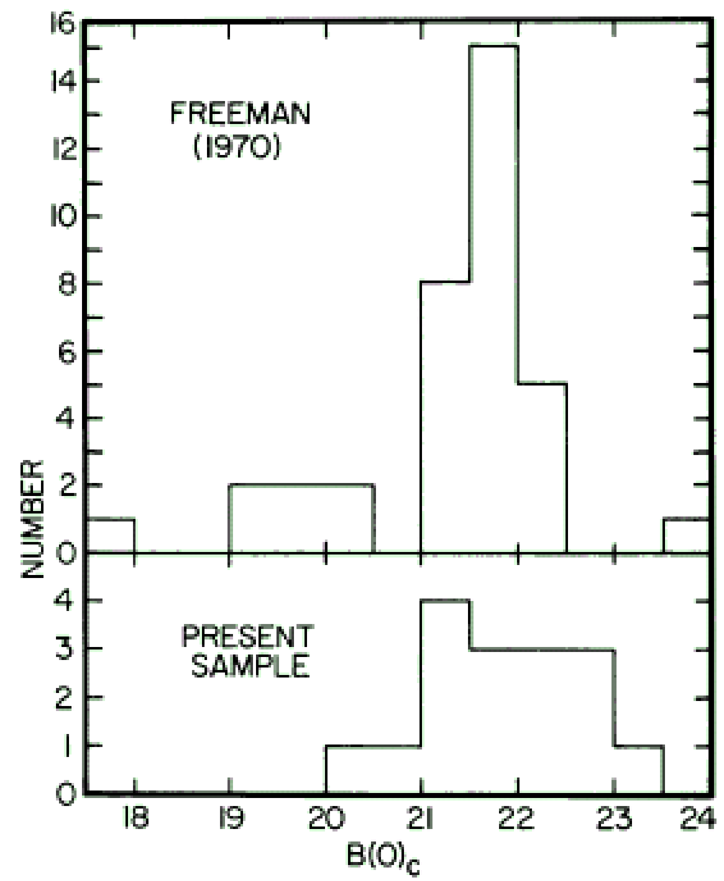
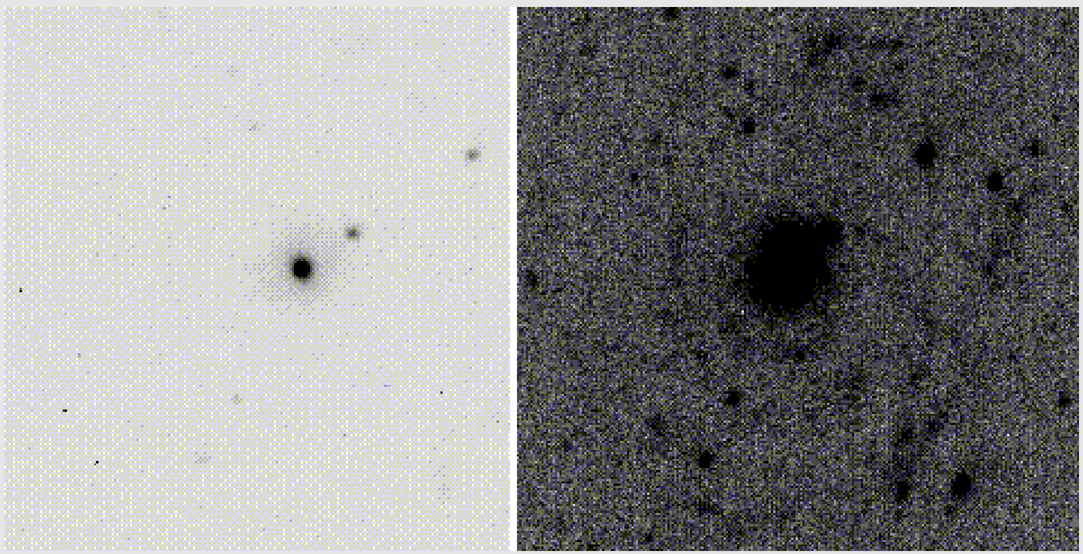
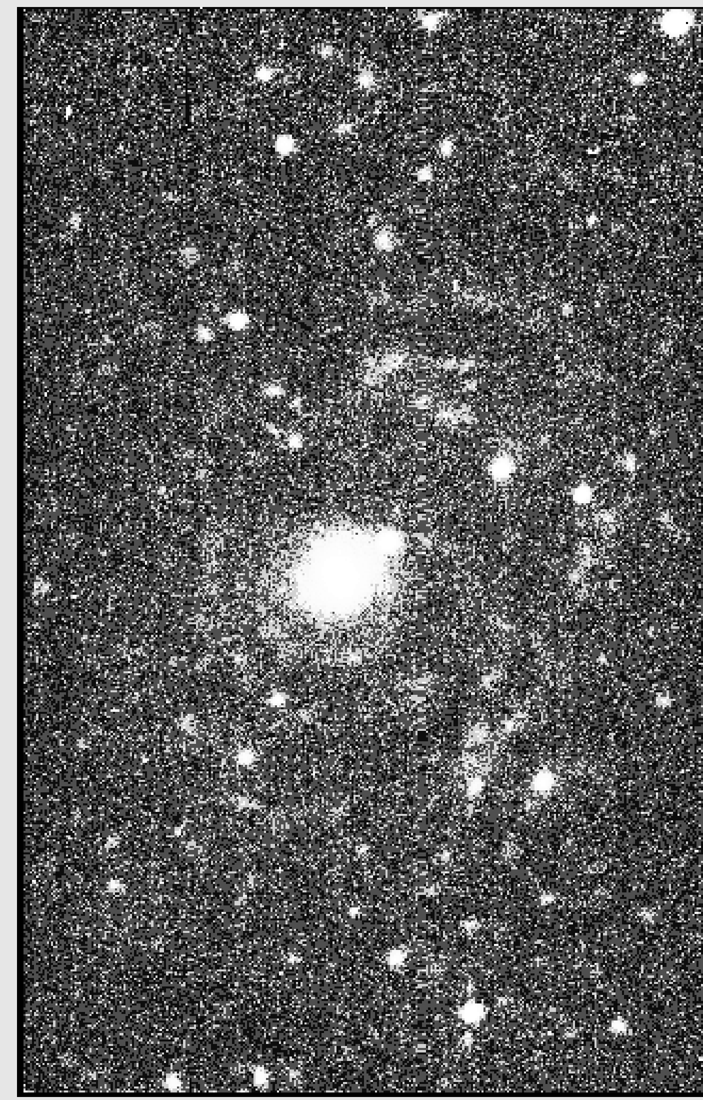


FIG. 7.—The distribution of disk central surface brightness in this study (*lower panel*) and in the study of Freeman (1970) (*upper panel*).

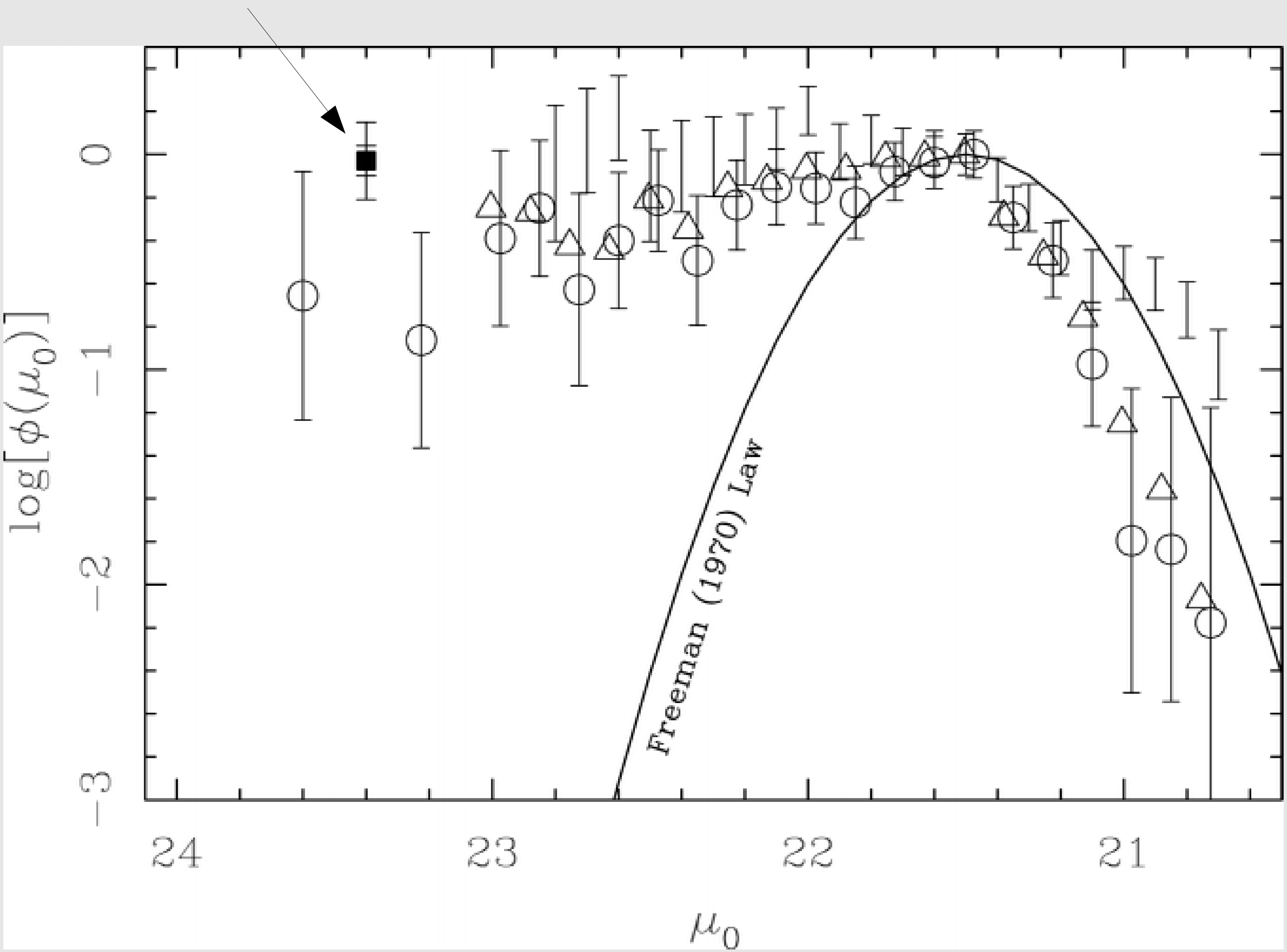
Low Surface Brightness Galaxies



Malin I



We now know that there are many LSB galaxies like Malin I.



Simien & de Vaucouleurs (1986) showed that the B/D decreases with T type

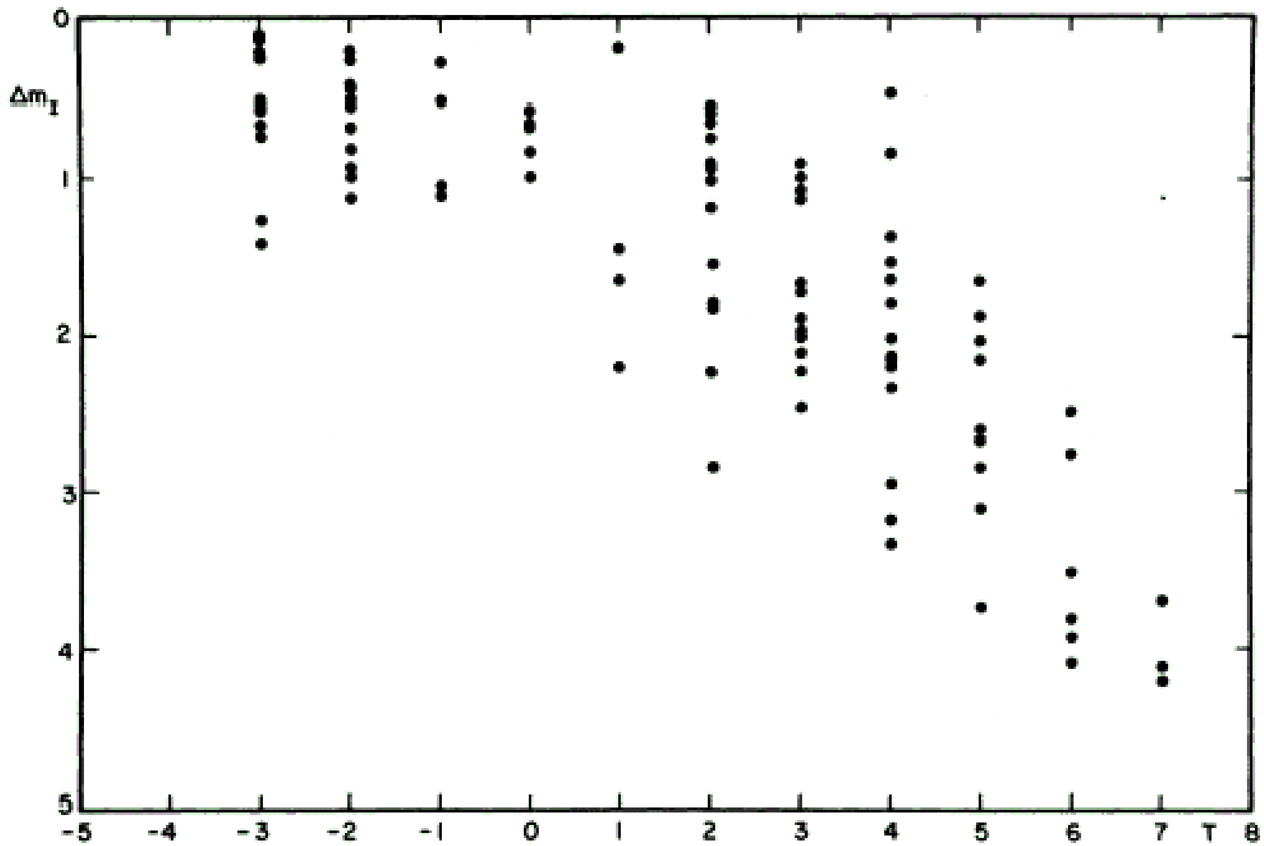
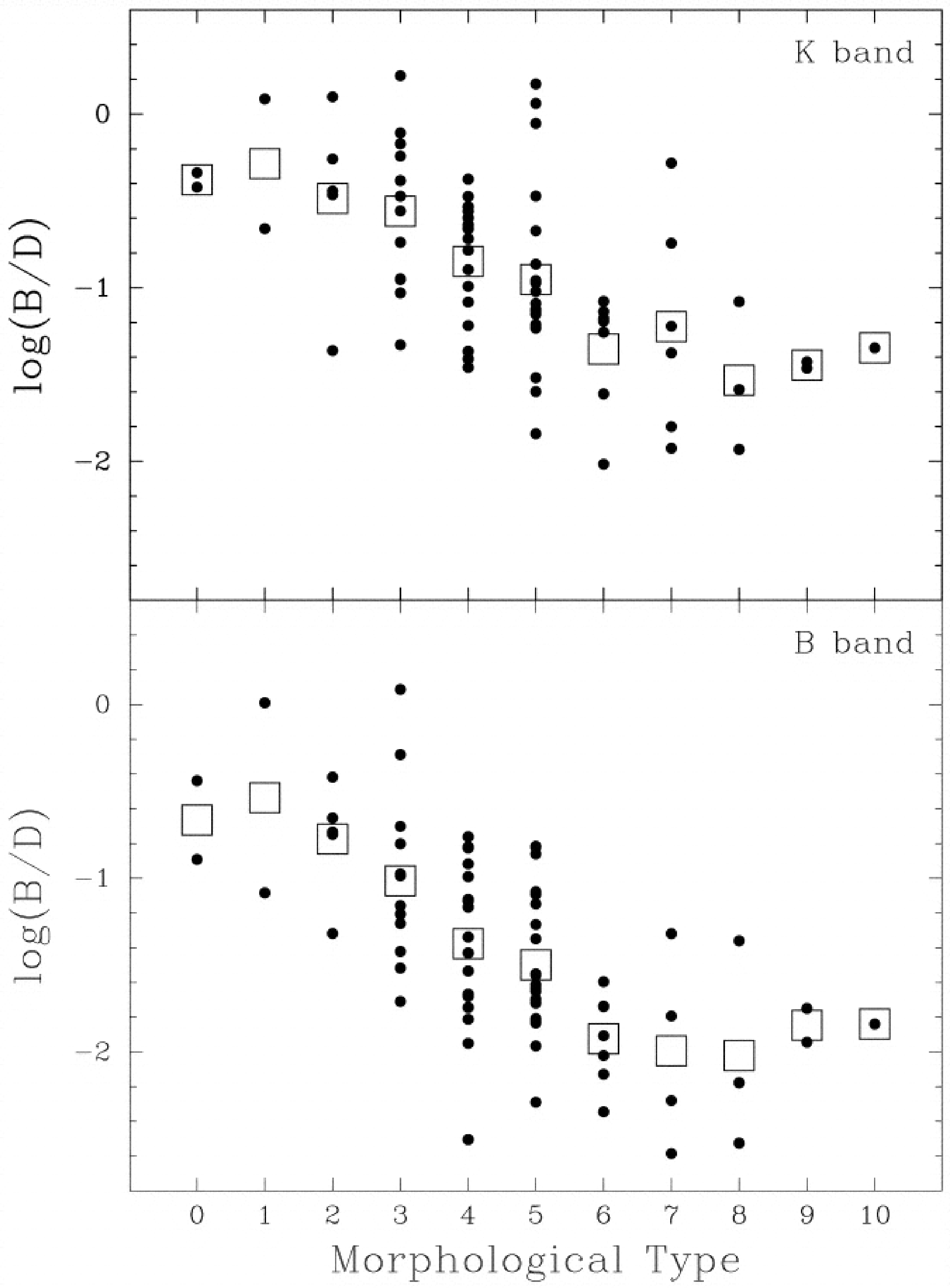


FIG. 2.—Fractional luminosity of spheroidal component expressed as magnitude difference $\langle \Delta m_I \rangle$ between spheroid and galaxy as a whole. Individual values vs. morphological type T (stage along revised Hubble sequence). Most of the scatter ($\sigma \approx 0.7$ mag) is due to photometric and decomposition errors, with little contributions from classification errors or cosmic scatter.

Modern data show this same trend and that T types > 7 this flattens (Graham 2001)



Inclination Effects

- When we integrate the SB profile to derive the total magnitude we need to correct for effects of inclination
  - We need to correct for
    - Dust
      - Internal (MW) and in the galaxy
      - Inclination (i=0 face on, i=90 edge on)
  - We get total correct magnitude B_T^0
  - Corrected colors are denoted by $(b\text{-}V)^0$
  - Assuming a thin disk, cos i = b/a, a = major axis and b = minor axis radius

The effects of dust attenuation is clearly most severe for highly inclined systems as Pierini et al. (2004) show.

Giovanelli et al (1994) show that the internal absorption can be modeled by $A_v = 1.12(+/-0.05)\log(a/b)$

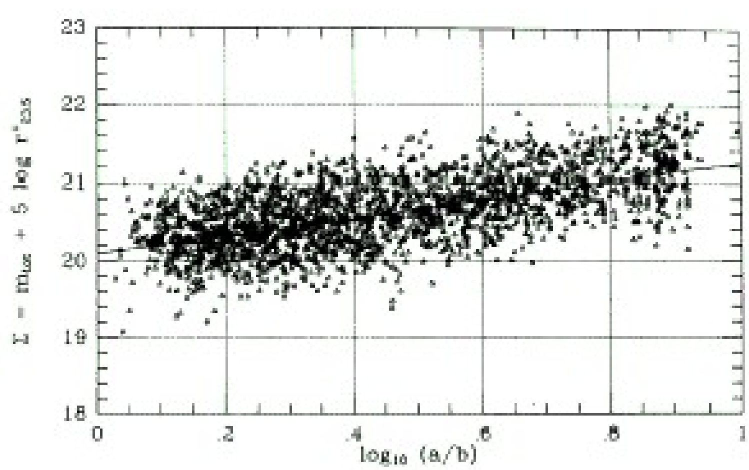
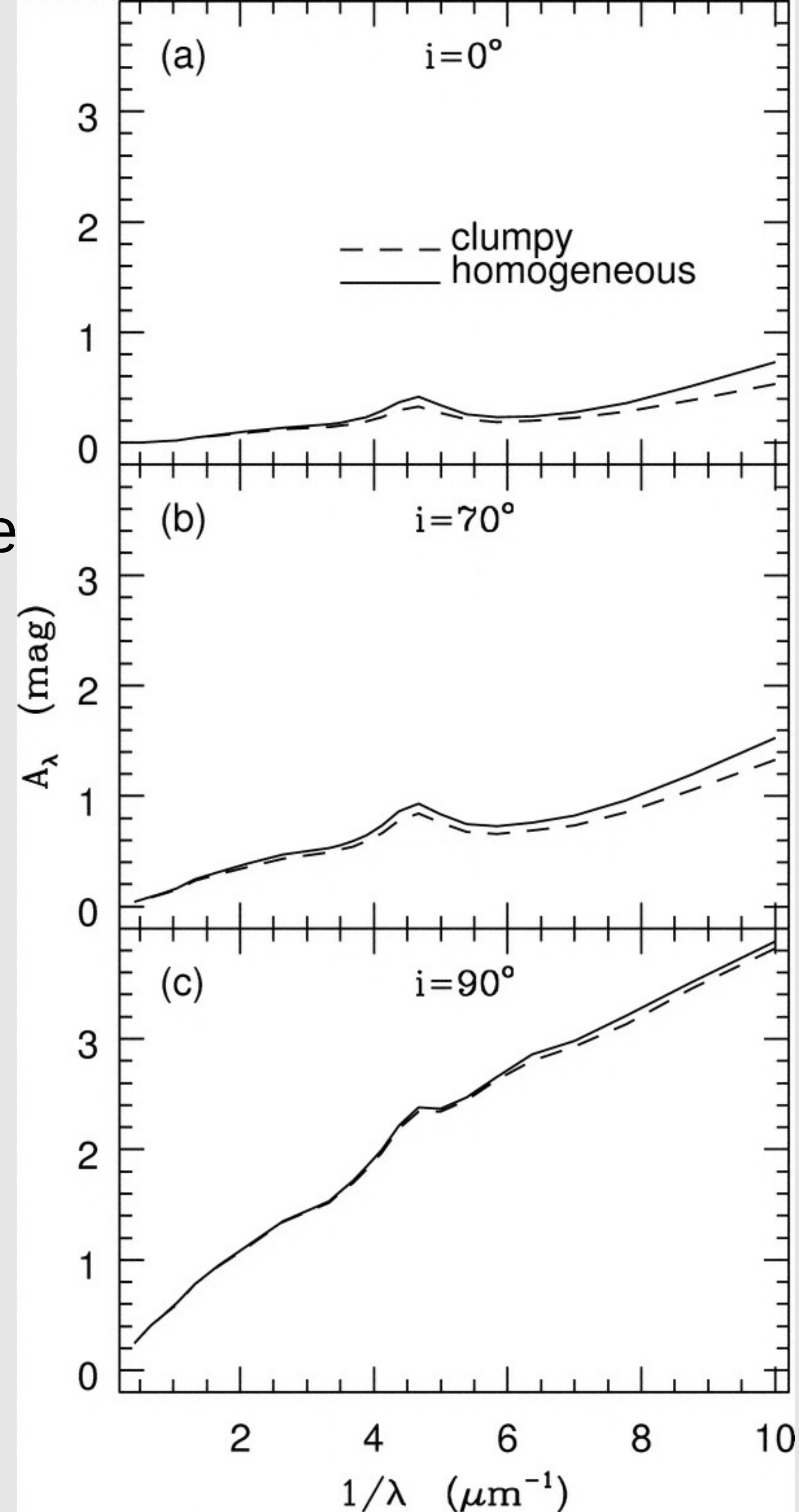


FIG. 17. Surface magnitude—obtained from the total magnitude m_{tot}—averaged over a circular aperture of radius $r^{o}_{23.5}$ vs log of the axial ratio. The filled circles are local averages and the solid line is a linear fit to the averaged values, with parameters given in Eq. (28). This relationship is obtained for galaxies in the expanded sample of 2272 objects.



Cartesian Coordinates

$$\nabla^2 \psi(x, y, z) = \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial \psi^2}{\partial z^2}$$

Polar Coordinates

$$\nabla^2 \psi(\rho, \phi, z) = \frac{\partial^2 \psi}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial \psi}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 \psi}{\partial \phi^2} + \frac{\partial^2 \psi}{\partial z^2}$$

Spherical Coordinates

$$\nabla^2 \psi(r, \theta, \phi) = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \frac{\partial \psi}{\partial r}) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}(\sin\theta \frac{\partial \psi}{\partial \theta}) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 \psi}{\partial \phi^2}$$