Disk galaxies

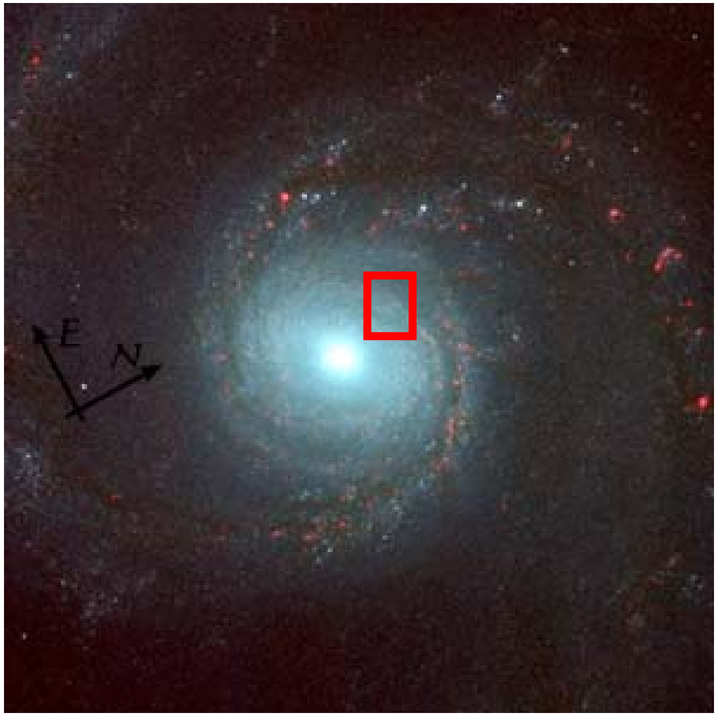
- Photometry of galaxies
  - surface brightness profile
    - components
  - effects of dust
  - colors /gradients

- Distribution of gas: HI

- Dynamics / kinematics: HI (no absorption by dust)
  - how is this measured
  - rotation curves
  - dark-matter

Galaxy photometry

The surface brightness of a galaxy $I(\mathbf{x})$ is the amount of light on the sky at a particular point $\mathbf{x}$ on the image.



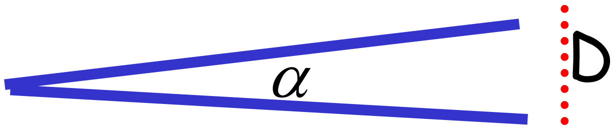
A small patch of side D in a galaxy located at a distance d, will subtend an angle $\alpha = D/d$.
If the combined luminosity of all the stars is L, its apparent brightness (received flux) is
$F = L/(4\pi d^2)$.

Therefore the surface brightness

$$I(\mathbf{x}) = F/\alpha^2 = L/(4\pi\, d^2) * (d/D)^2 = L/(4\pi\, D^2).$$

<u>The surface brightness is independent of distance</u>

- not true for cosmological distances



The units of $I(x)$ are $L_\odot/pc^2$, or equivalently energy/sec/arcsec^2

Quite often the magnitude is quoted instead of the flux at a given point on an image. In this case, the surface brightness:

$$\mu_\lambda(x) = -2.5 \log_{10} I_\lambda(x) + cst_\lambda$$

The units of μ are [mag/arcsec^2.]

The constant cst_λ is set to have a value of 26.4 mag/arcsec^2 in the V-band.

This magnitude corresponds to 1 $L_{\odot V}/pc^2$. Therefore,

$$I_V = 10^{0.4\,(26.4 - \mu_V)}\, L_{\odot V}/pc^2$$

Galaxy photometry

The total (apparent) magnitude of the galaxy is:

$$m = -2.5 \log_{10} \int d\phi \, R \, dR \, I(R,\phi) \; + \; cst$$

which for a circularly symmetric galaxy, reduces to

$$m = -2.5 \log_{10} \int R \, dR \, I(R) \; + \; cst'$$

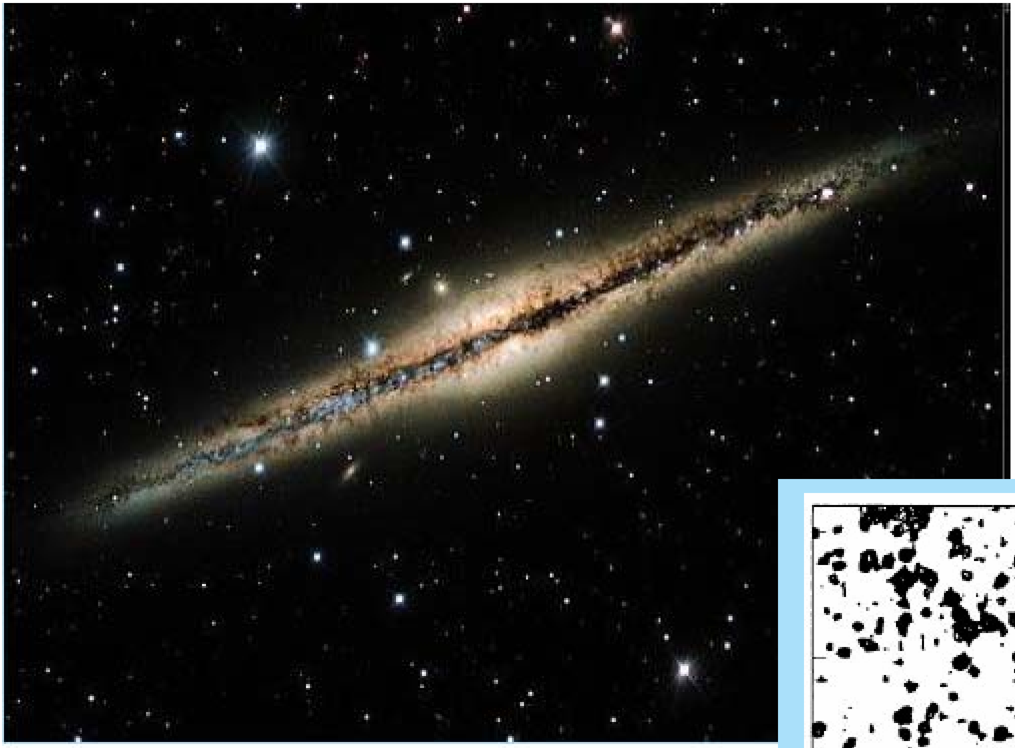
Often integrated magnitudes are measured up to the radius of a given magnitude, usually 26 m_B.

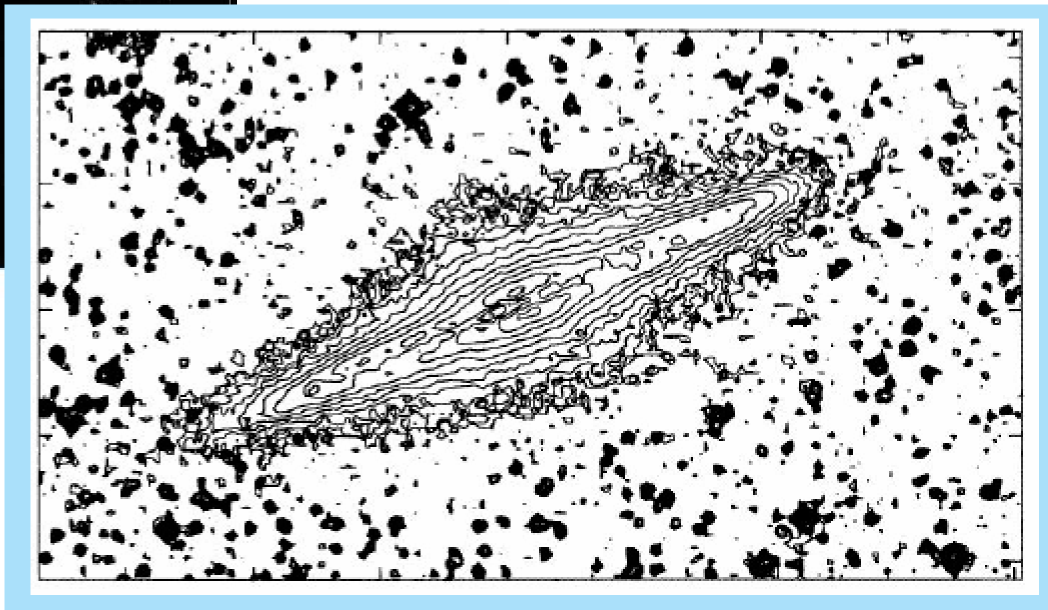
Note that distance is needed to derive its absolute magnitude.

Contours of constant surface brightness on a galaxy image are known as *isophotes*.

Isophotes

Contours of constant surface brightness on a galaxy image are known as *isophotes*.





Photometry of disk galaxies

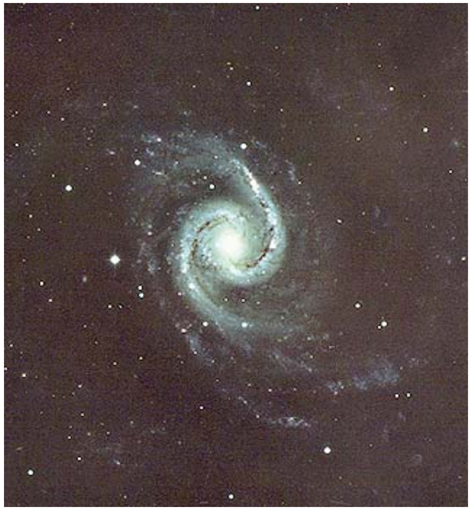
The surface brightness profiles of disk galaxies are complex:

- more than one component (central bulge, disk, bar, spiral arms, rings…),
- large amounts of dust (not transparent)

Their appearance depends both on the stellar distribution and that of gas and dust, and on the angle from which we observe them.

Edge on: $i = 90^o$

Face on $i = 0^o$

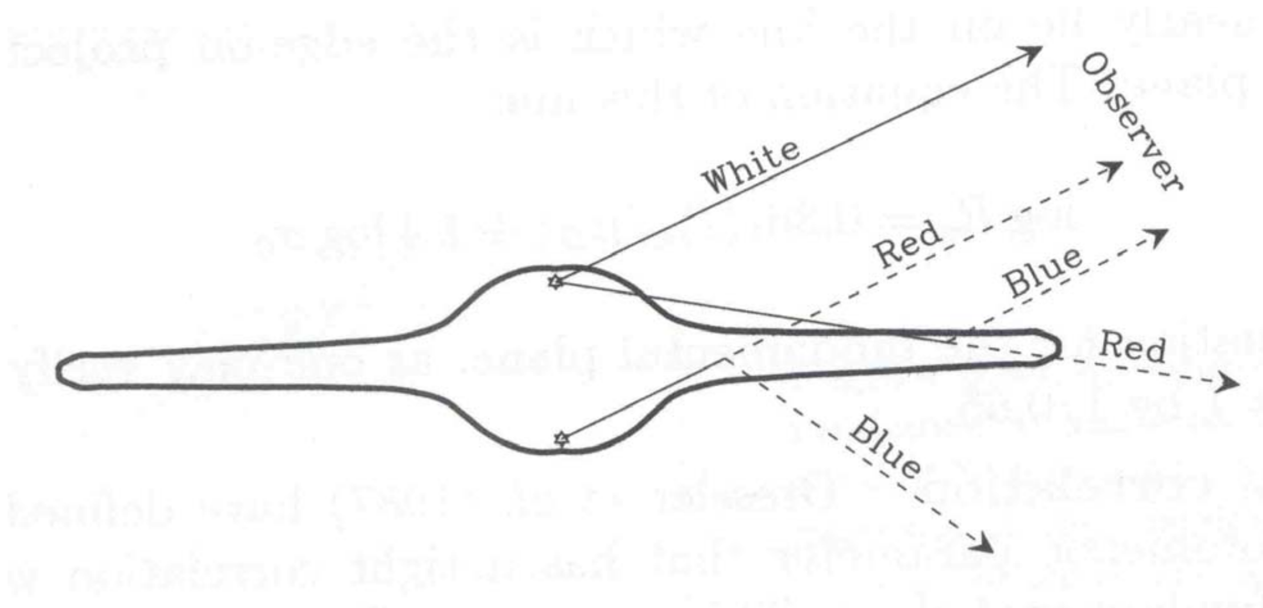


Photometry of disk galaxies: dust

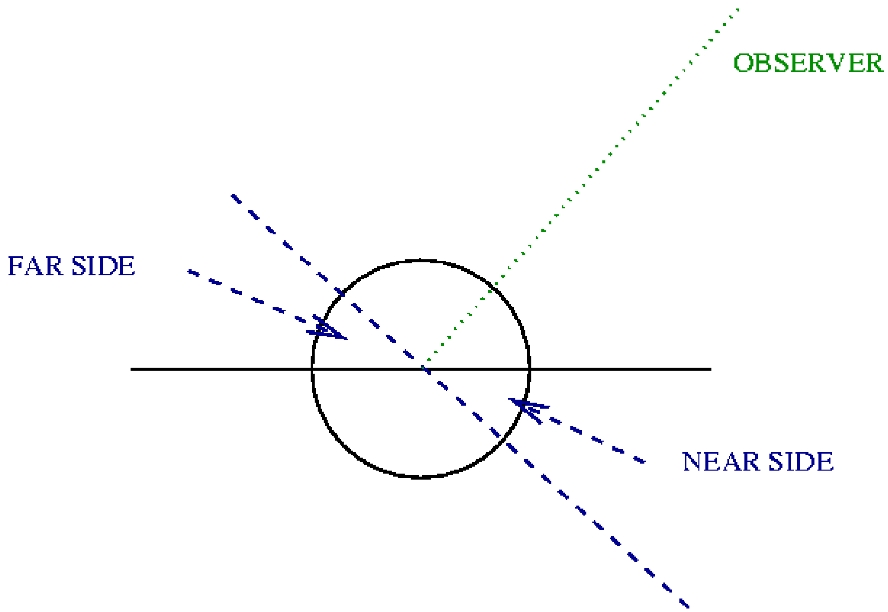
The large amounts of dust affect the surface brightness (flux per arcsec^2), depending on the angle:

•edge-on: light has to pass through larger columns of the galaxy's interstellar material

•various components are affected differently

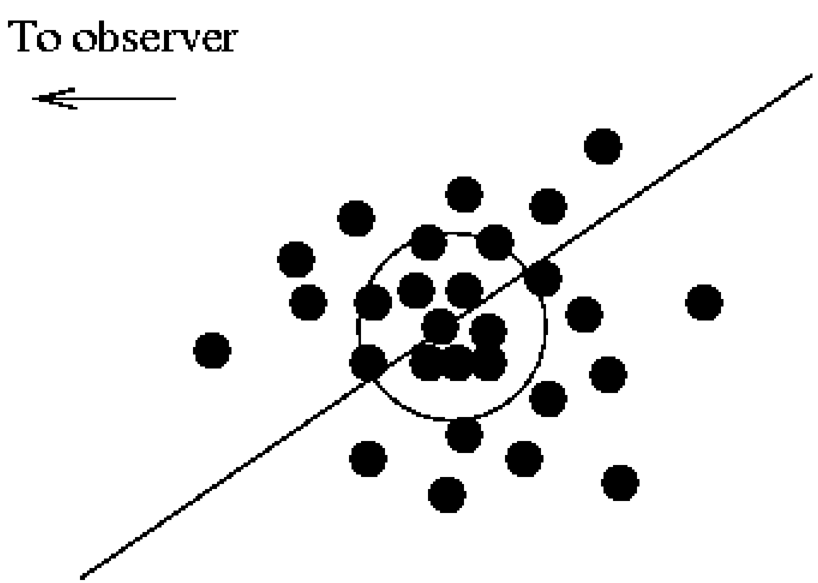


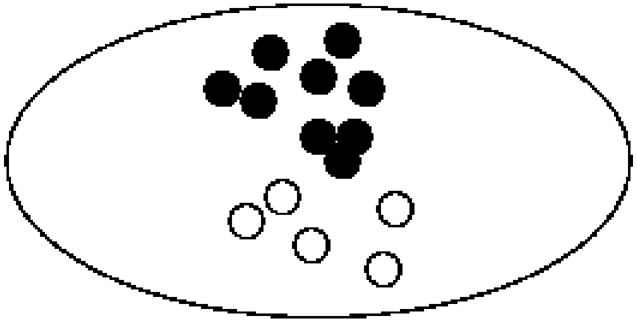
Effect of absorption



Light from the near side of the bulge (along the major axis) is absorbed by the dust in the disk.

Near side is redder than far side of the bulge.





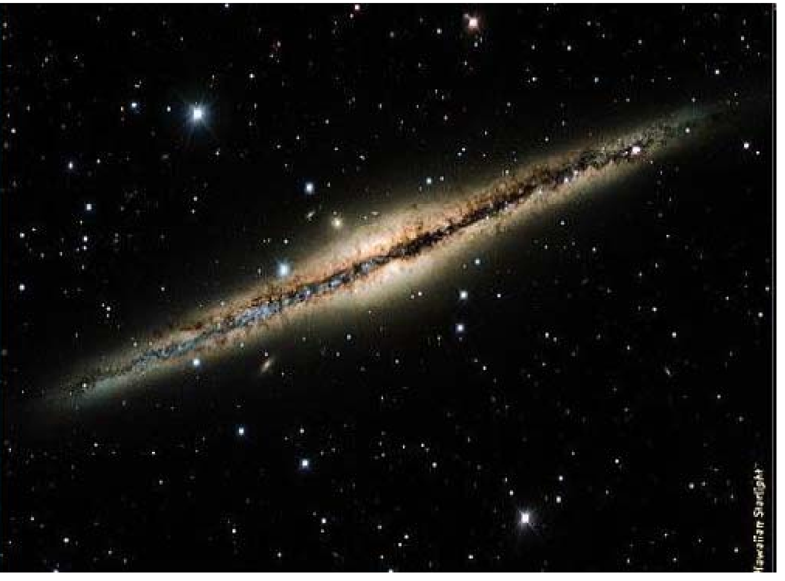
Effect of scattering

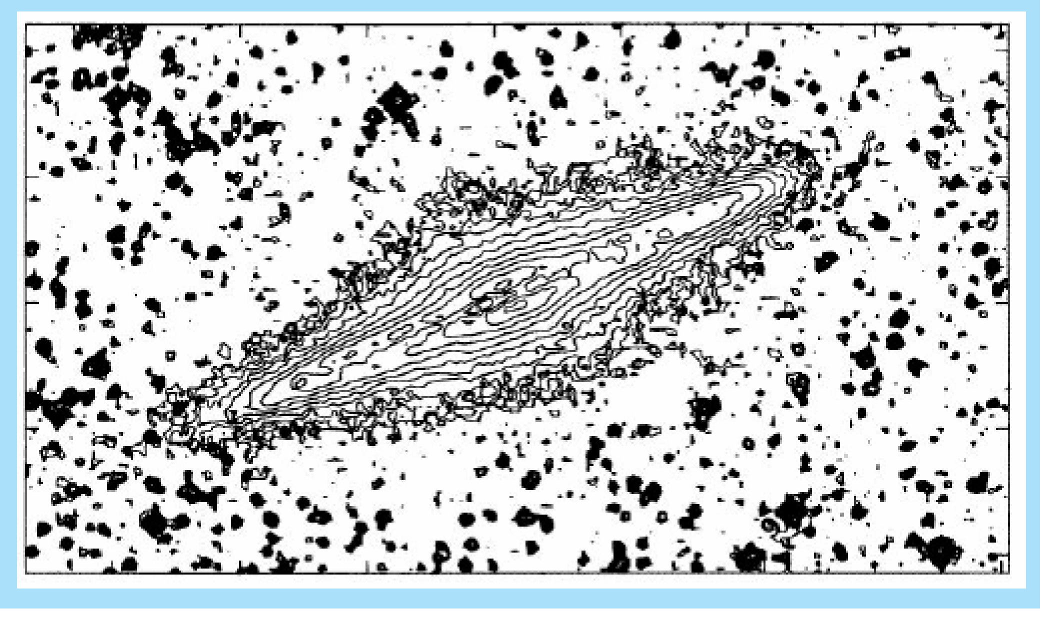
- Dust preferentially scatters blue light.
- Light from the near side is more scattered than that on the far side.
- The near side appears bluer.

Scattering is not isotropic; it is produced by dust grains that are not round. They are more efficient in scattering light through small angles (forward scattering).

- Scattering and absorption have competing effects.
- Dominant effect depends on the inclination of the galaxy:
    - at small inclinations (nearly face on) absorption dominates, the near side appears dimmer and redder.
    - At intermediate inclinations, (forward) scattering dominates.
    - At very large inclinations, the near side is very heavily obscured.

Photometry of disk galaxies

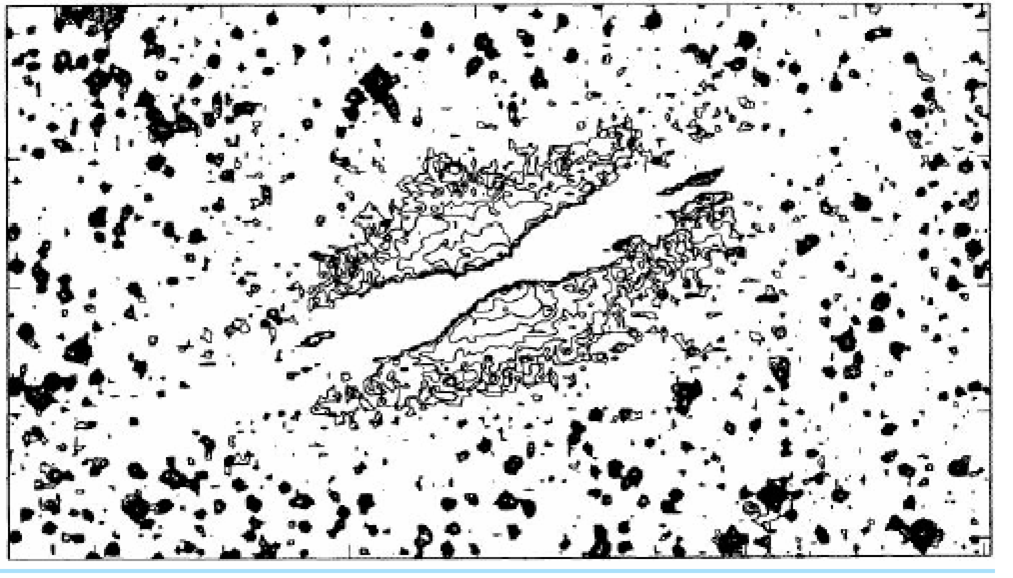




Steps:

•isophotes are fitted
•profile along major axis and minor axes

•disk component is subtracted
•bulge component is fitted

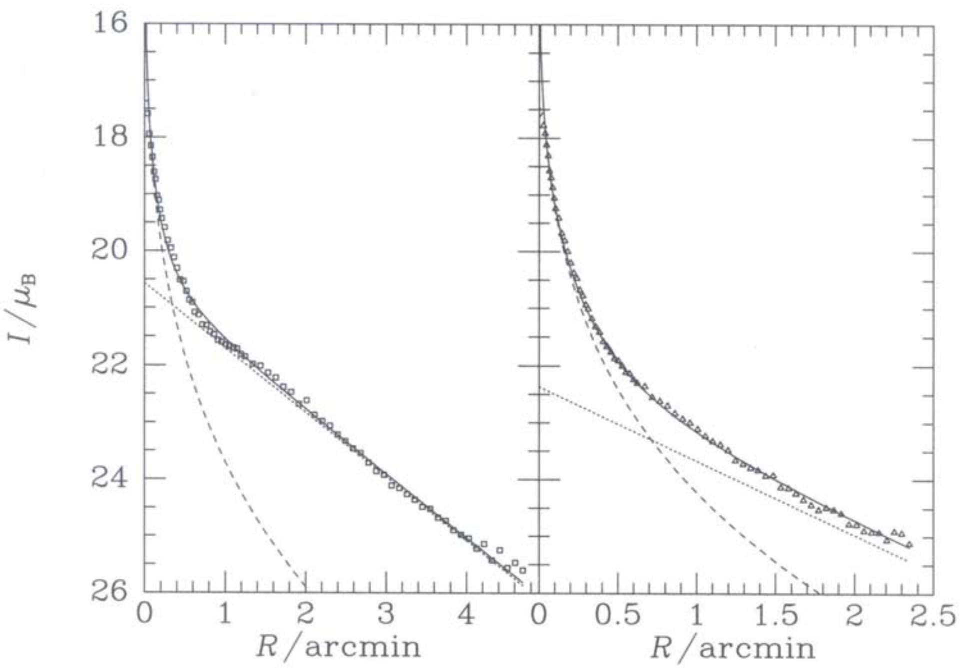


Photometry of disk galaxies

•At large distances from the center, the surface brightness profiles are straight lines in a log-linear plot (log intensity -magnitude- vs. radius).

•The profiles decay exponentially: $\mu(R) = \mu(0)\exp[-R/R_d]$

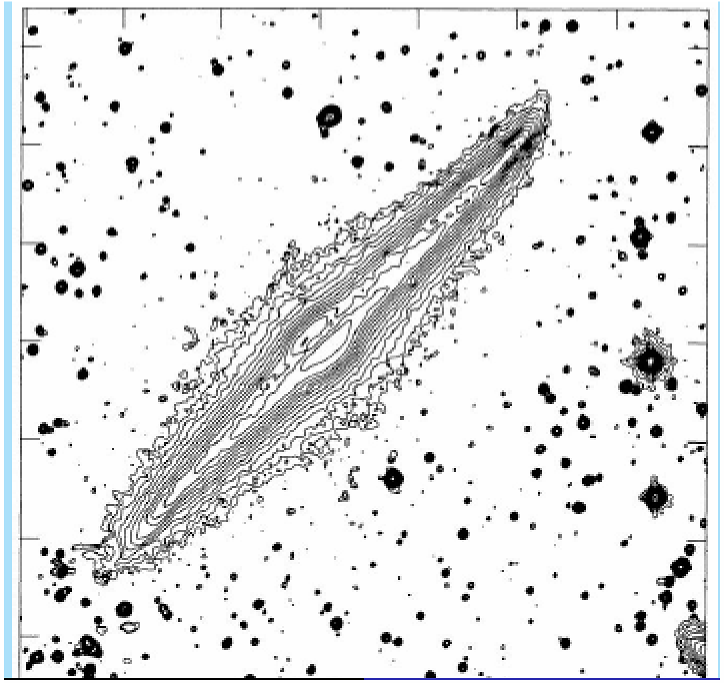
•Deviations from this behavior can often attributed to the presence of other components in the disk (e.g., bars and rings).

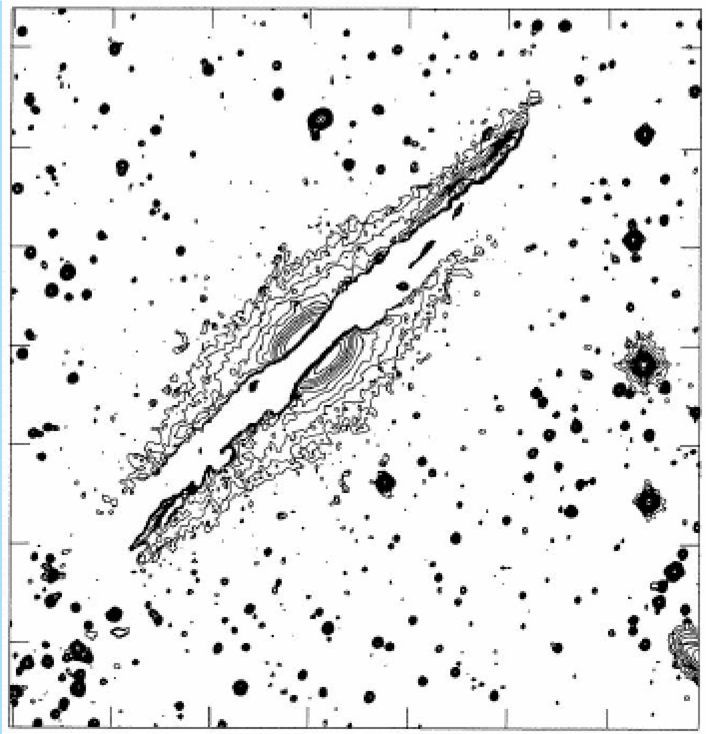


Dotted line: exponential fit to the disk

Dashed curve is an $R^{-1/4}$ profile fitted to the central bulge of these galaxies.

The full curve is the "sum" of both components.





Sometimes warps are visible in the isophotes

For edge-on galaxies can derive the light profile perpendicular to the plane of the disk (z-direction).

Commonly used profiles are:

$$j(R,z) = j_0 \exp(-R/R_d)\exp(-|z|/z_0)$$

$$j(R,z) = j_0 \exp(-R/R_d)\,\mathrm{sech}^2(z/2z_0)$$

Typically $z_0 \sim 0.1\ R_d$

Sometimes a second exponential component can be fitted to the observed light distribution of edge-on galaxies (the equivalent of our thick disk).

This is hard: inclination effects, a very flattened stellar halo, etc, all can mimic a thick disk.

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 expressed by the Sersic law:

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

Recall that
- n=1 corresponds to an exponential
- n=4 is the de Vaucouleurs law (typical of large E galaxies).

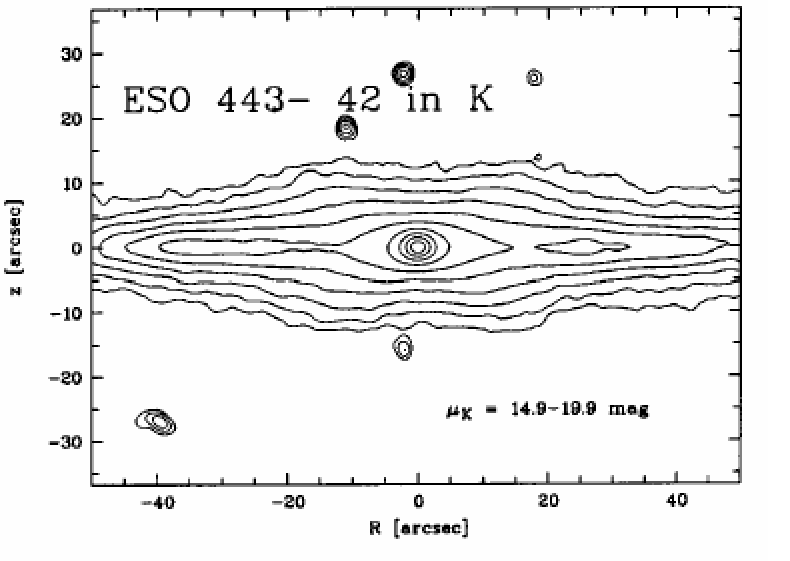
Bulges

•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: boxy shape (not round) of the light distribution.

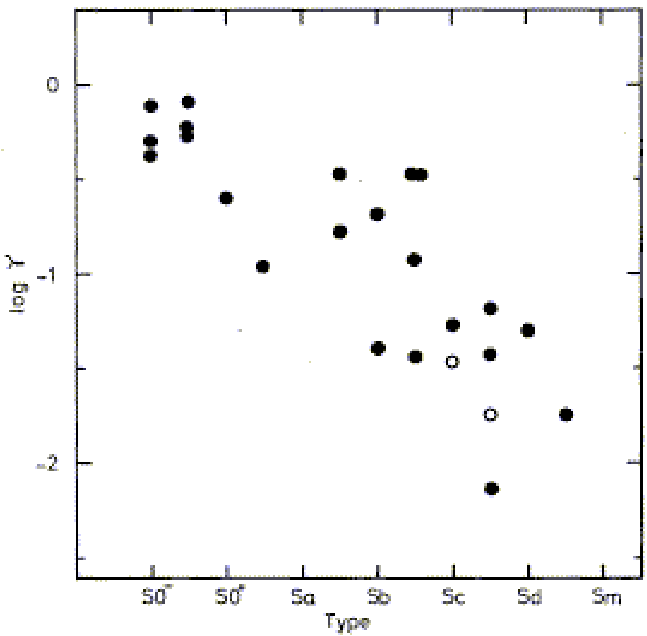
In some cases the isophotes are squashed, and the bulge/bar has a peanut-like shape.



In the general case, the total surface brightness profile can be expressed as a combination of the bulge and an exponential (the disk) profile.

The relative contribution of the bulge to the total luminosity is known as the bulge fraction:

$$B/T = \frac{R_e^{\ 2} I_e}{R_e^{\ 2} I_e + 0.28 R_d^{\ 2} I_d}$$

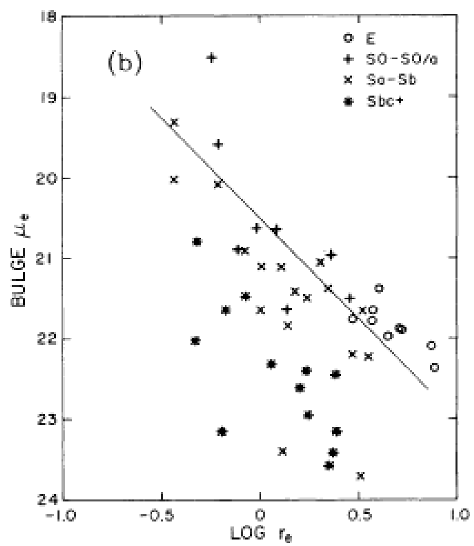


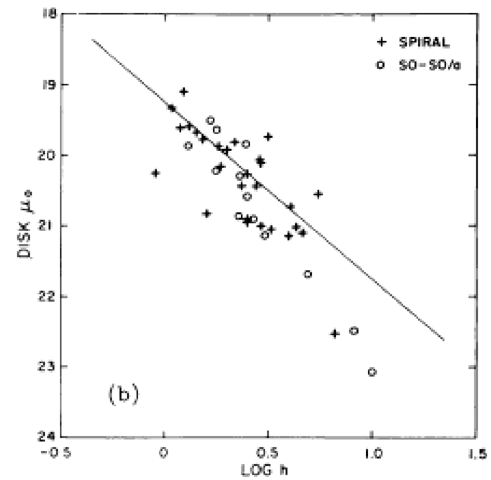
This ratio is computed from the total luminosity of the bulge (for an R^{1/4}) and the disk (exponential in R).

This is related to the disk-to-bulge ratio: $D/B = (B/T)^{-1} - 1$

B/T (or γ = B/D) correlates Hubble type.

Correlations between parameters





•Bulges of Sb and earlier type disks follow similar relation between central surface brightness and effective radius as E galaxies.

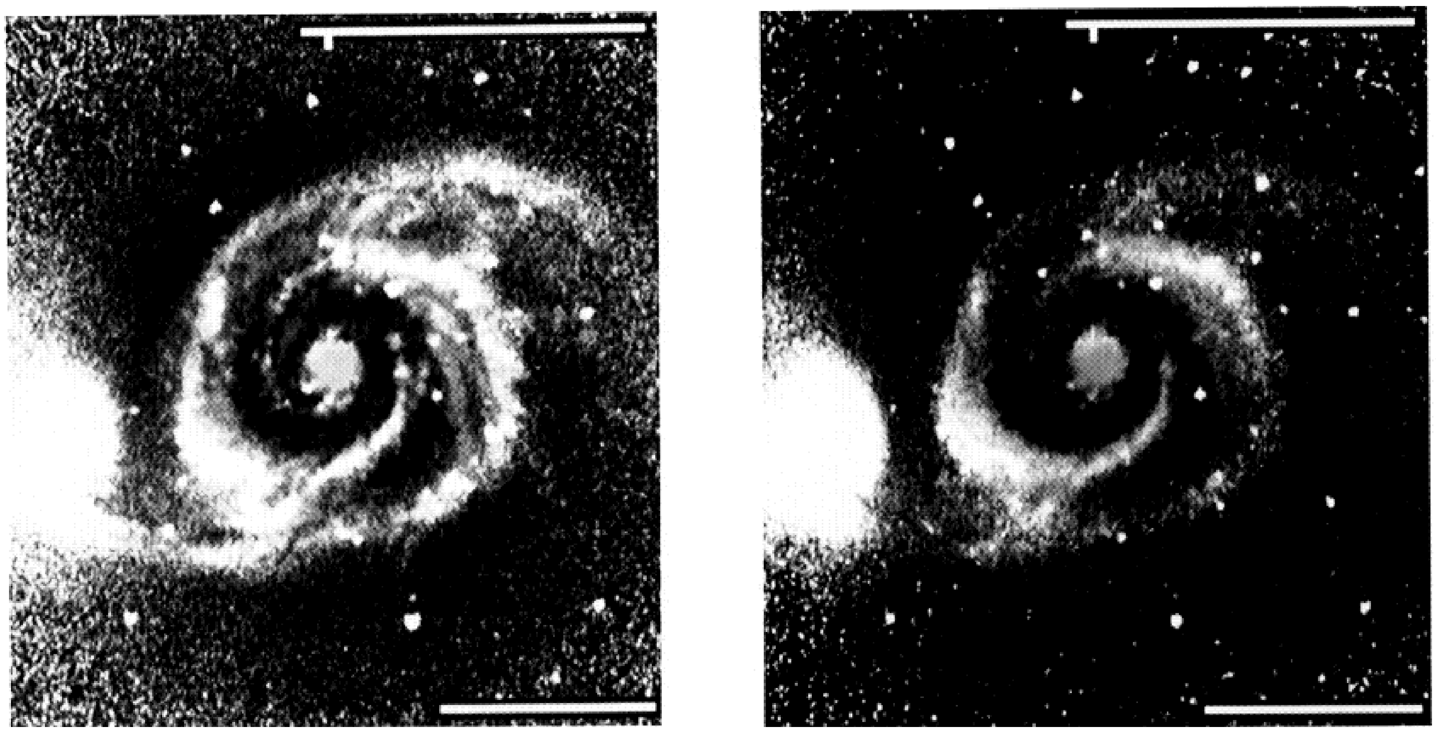
•Bulges of later types (Sc…) lie systematically lower.

•The disks also show that physically larger systems have lower central surface brightness.

Spiral structure

Subtract azimuthally smooth component to enhance the spiral pattern

M51 (left panel in the B band, right panel in the I-band)



These images show that

(i) spiral structure is present in both bands, but has larger amplitude in B band;

(ii) spiral structure is smoother in I than in the B band

Spiral structure and patterns

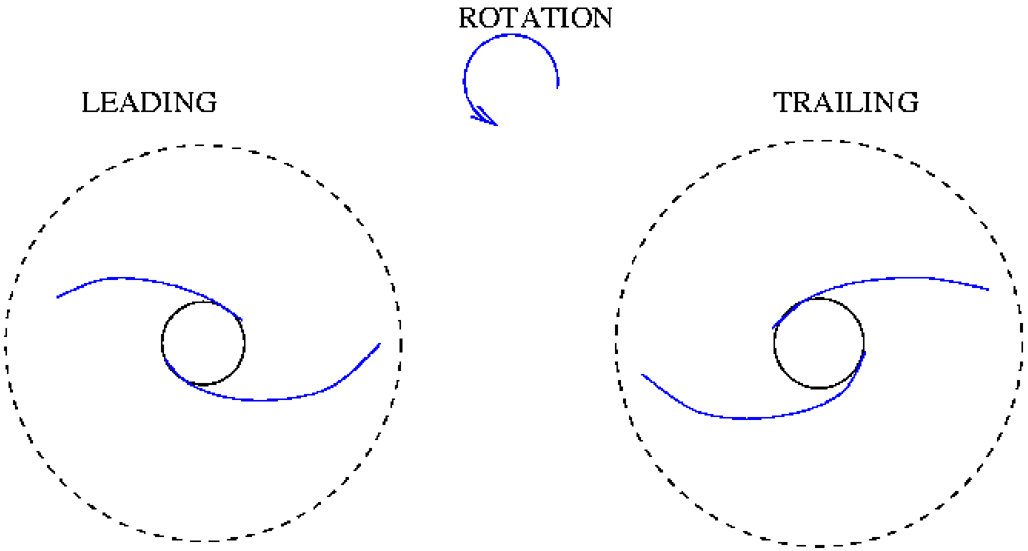
Shapes of spiral galaxies are approximately invariant under a rotation around their centres.

A galaxy that looks identical after rotation of $2\pi/m$ has m-fold symmetry.

A galaxy with an m-fold symmetry has m-spiral arms.
Most spirals have 2 arms, hence they have a twofold symmetry

Spiral patterns are classified according to orientation compared to rotation direction

- trailing
- leading

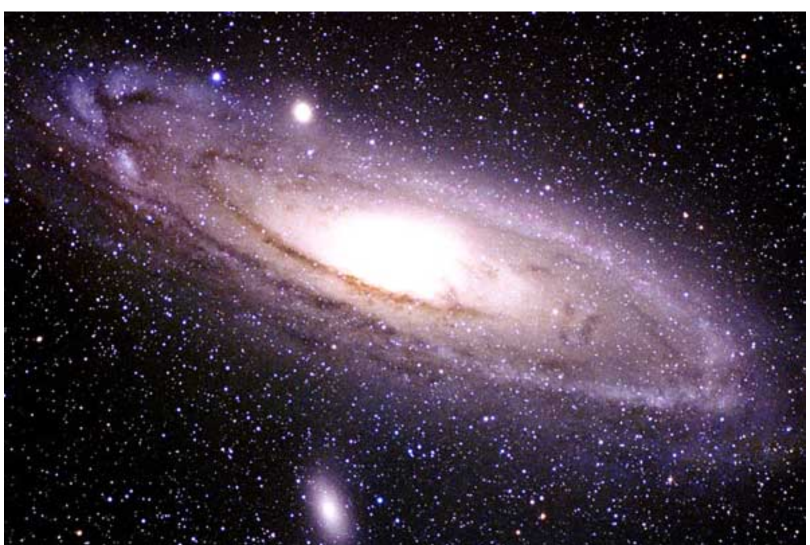


Colour and metallicity of disk galaxies

Consider M31:

- Interior to 6 kpc:
    - the bulge dominates the light
    - colours are similar to an E galaxy.

- Further out:
    - young stars contribute substantially to the surface brightness, and colour of the galaxy.



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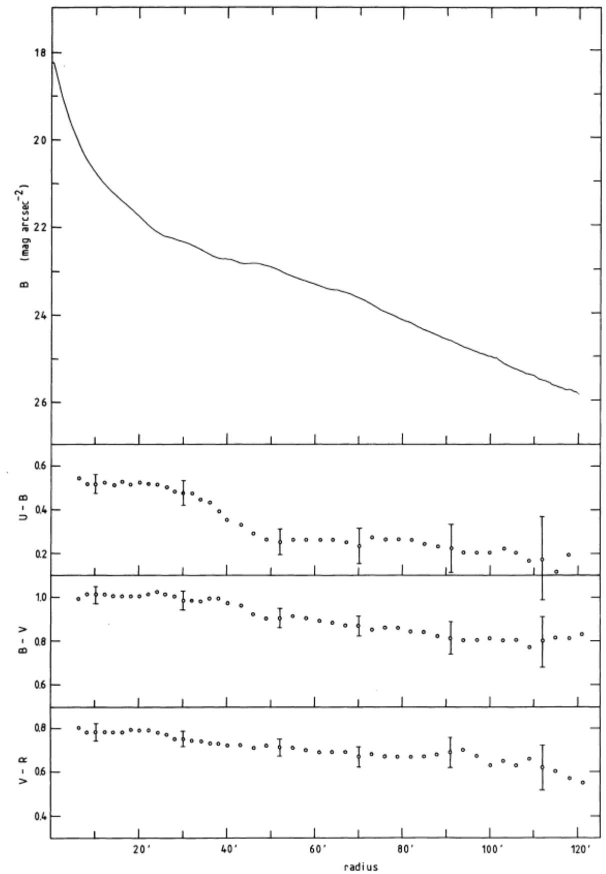


FIGURE 12. — The global light and color profiles of M31 obtained from the data by averaging the intensity distributions in ellipses centred on the nucleus of the galaxy. Foreground stars were removed from the data beforehand. The uncertainties were estimated from comparisons of the global profiles derived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

For other disk galaxies, there is no conclusive answer with respect to the presence or absence of colour-gradients (they are very hard to measure).

There are competing reasons for colour-gradients:

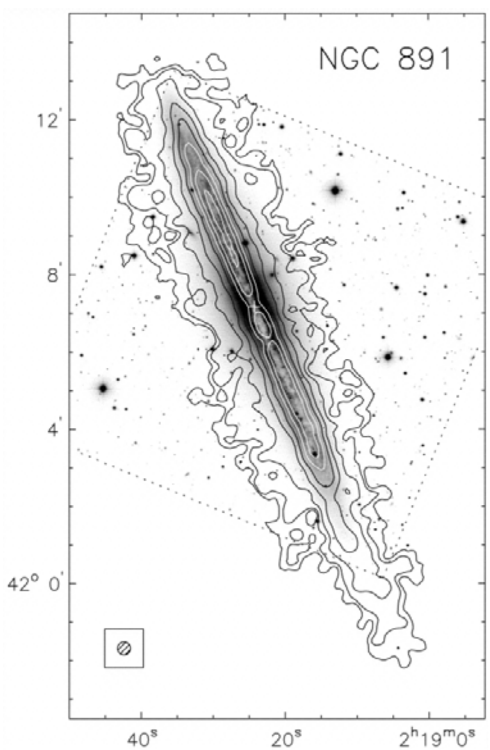
- the degree of internal extinction by dust
- the mean ages of stars
- metallicity gradients

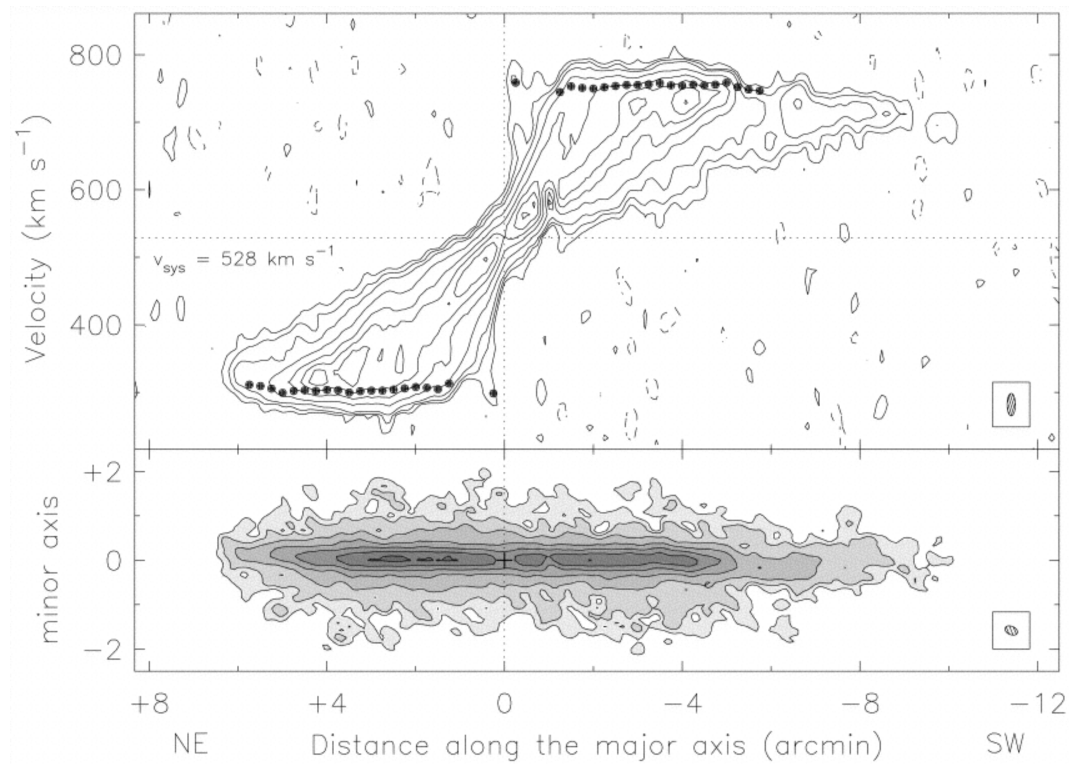
All of these effects could produce colour-gradients or destroy them

Cool gas in the disk

- Since the gas in the disk is moving, the emission of the HI 21 cm line will be Doppler shifted according to its radial velocity.

- The HI suffers little absorption by dust
    - .The mass of gas is simply proportional to the intensity of its emission.





Cool gas in the disk

- The HI gas is often spread out more uniformly than the stars:
    - peak (central density) is only a few times larger than average
    - in comparison there is a 10,000 contrast in stellar disks)
    - It can also be more extended.

- The ratio $M(HI)/L_B$ is used as an indicator of how gas rich a system is:
    - S0/Sa: 0.05 – 0.1 $M_{sun}/L_{B,sun}$.
    - Sc/Sd it is about ten times larger.

Gas motions

- For the Milky Way: stars and gas account only for a fraction of its mass.

- We introduced the concept of dark-matter.

- The same is true for most spiral galaxies.

The acceleration of a particle moving on a circular orbit is related to the gravitational potential $\Phi(R,z)$ acting on it:

$$\frac{V^2(R)}{R} = \left| \frac{\partial \Phi}{\partial R} \right|_{z=0}$$

- V(R) is the circular velocity (defined as in the Milky Way)

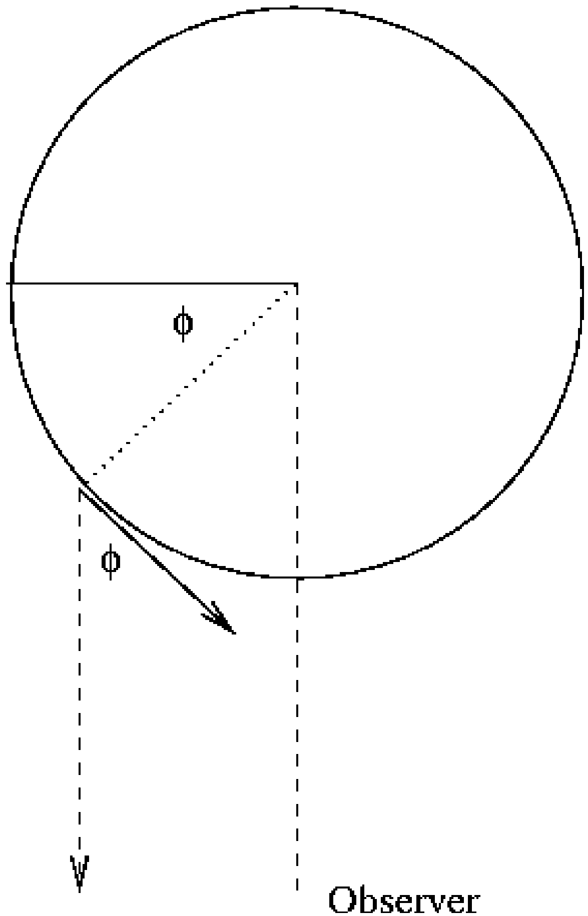
- It gives how the gravitational potential (and hence mass) varies as function of distance.

Rotation curves

- V(R) is often referred to as the rotation curve.
- The dominant motion in a disk galaxy is rotation (just as for the MW)
- HI gas random motions are typically of the order of 10 km/s or smaller.
- We assume that gas clouds follow nearly circular orbits with velocity V(R)

How is V(R) derived from the observed radial velocity of the gas??

Rotation curves: edge-on



Viewed edge-on, the radial velocity measured $V_r(R,i=90)$ is

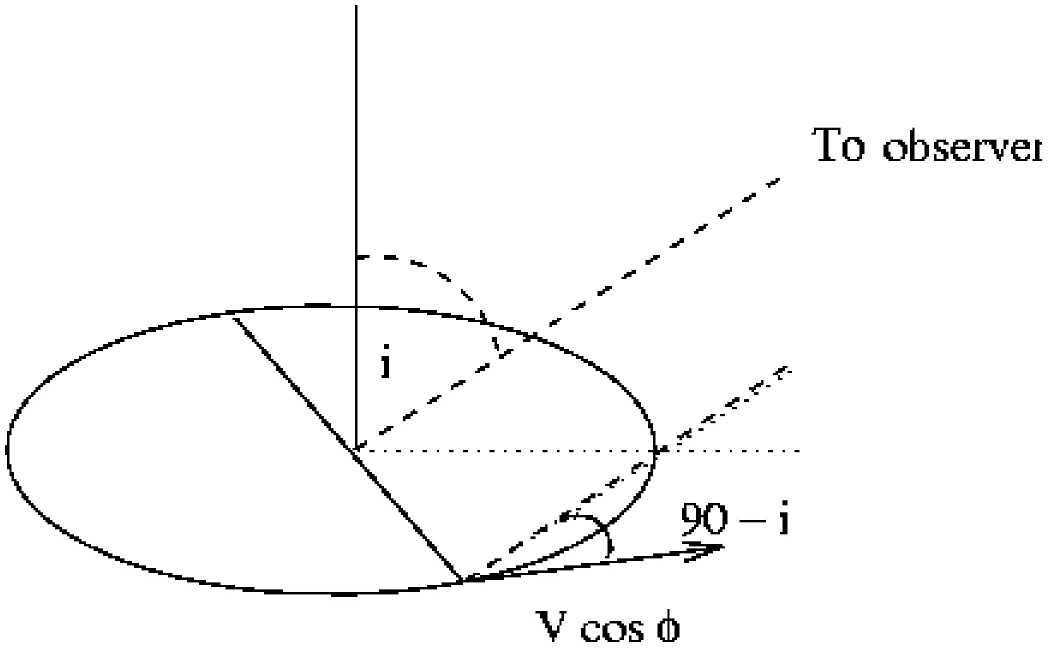
$$V_r(R,i=90) = V_{sys} + V(R)\cos\phi$$

V_{sys} is the systemic velocity of the Galaxy wrt the observer.

When the galaxy is tilted an angle *i*, one additional projection is needed

The measured radial velocity $V_r(R,i)$ is

$$V_r(R,i) = V_{sys} + V(R) \cos\phi \sin i$$



Spider diagrams

Contours of constant V_r connect points with the same value of $V(R) \cos\phi$

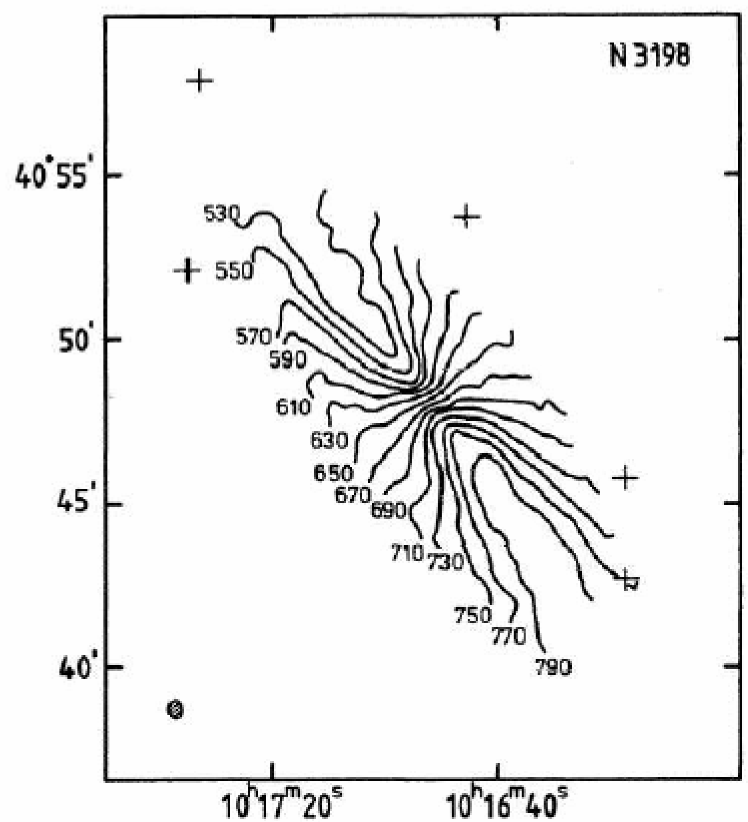
Gives rise to a spider diagram

- In the central regions, the contours are parallel to the minor axis.

- Further out, (i.e. larger values of ϕ), they run radially away from the centre.

- The kinematic major axis: where the radial velocity deviates most from the systemic velocity of the galaxy (i.e ϕ=0,180 deg)

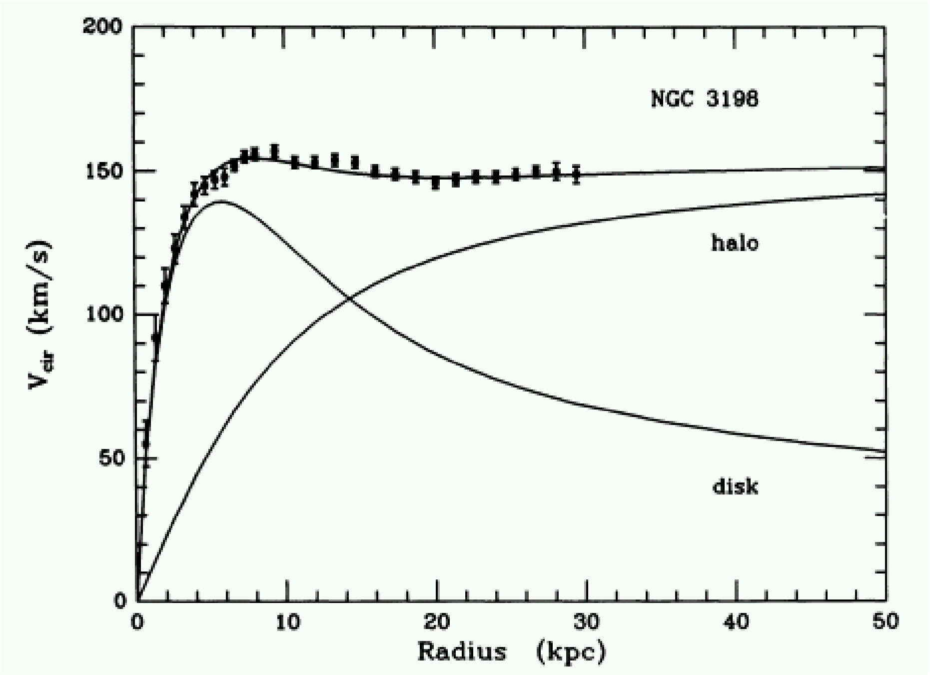
- The more closely packed the contours are, the more rapid the fall off in V(R)



This is the rotation curve for the previous galaxy.

It is shown as function of radius R along the (photometric) major axis.

This axis is generally (but not always) coincident with the kinematic major axis.



We can compare this rotation curve to that provided by the luminous mass in the galaxy.

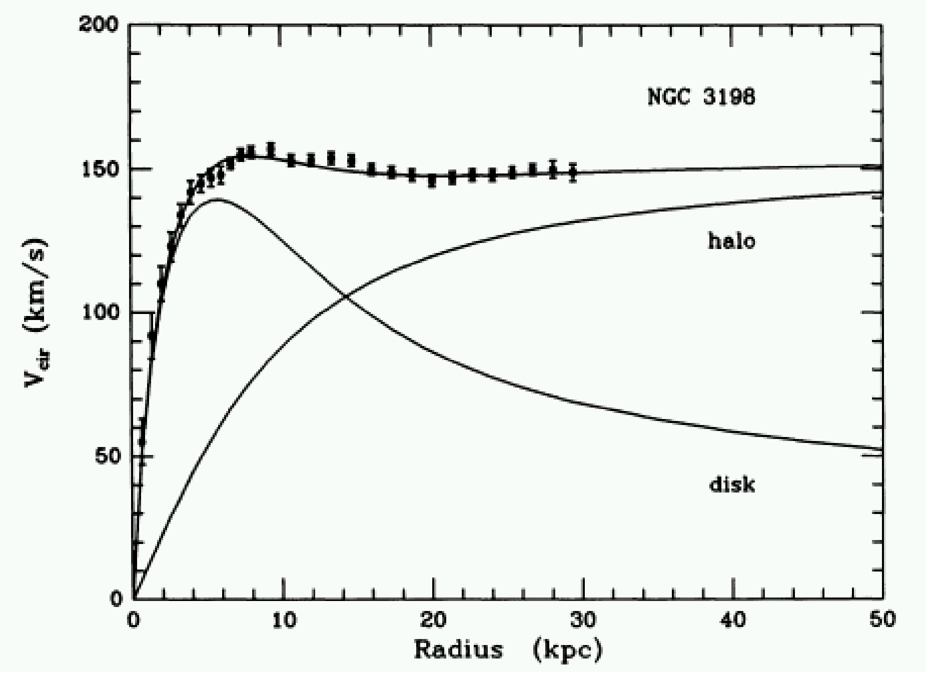
To calculate the predicted circular velocity we use the observed surface brightness distribution of gas and of stars

(preferably in R-band to be sensitive to older stellar populations which trace mass better).

Fitting rotation curves

•V(R) depends on mass (and not on luminosity or brightness):
•transform surface brightness into surface density:
•assume a M/L (mass-to-light ratio).

Typically, one uses values of M/L found in the Solar neighbourhood. M/L ~ 1-3 $(M/L)_\odot$.



The contribution of the bulge and disk:

$$V^2(R) = V^2_{disk}(R) + V^2_{bulge}(R)$$

since the potentials (or the forces) can be added linearly.

Dark matter in disk galaxies

- It is necessary to add a third component to the galaxy, a "dark halo".

- This component is more extended and dominates at large radii.

- The dark halo accounts for a large fraction of the total mass of a galaxy
    - In Sa/Sb galaxies, the proportion of dark-matter needed is ~ 50%
    - In Sd and later, this increases to 90%.

- The mass derived from rotation curves, is a lower limit

    - The rotation curve as measured by HI kinematics, can only probe regions of the galaxy where there is an HI disk

    - Most of the dark matter is expected at larger radii.

    - To measure it requires tracers that probe those regions, such as satellite galaxies, binary pairs, planetary nebulae etc.

Uncertainties and degeneracies. I

• There is no unique decomposition for a given a certain rotation curve

• Different functional forms for the dark-matter distribution can be consistent with the data

Some examples are:

- isothermal profile: $\rho(r) = \rho_0 \, (r_0/r)^2$

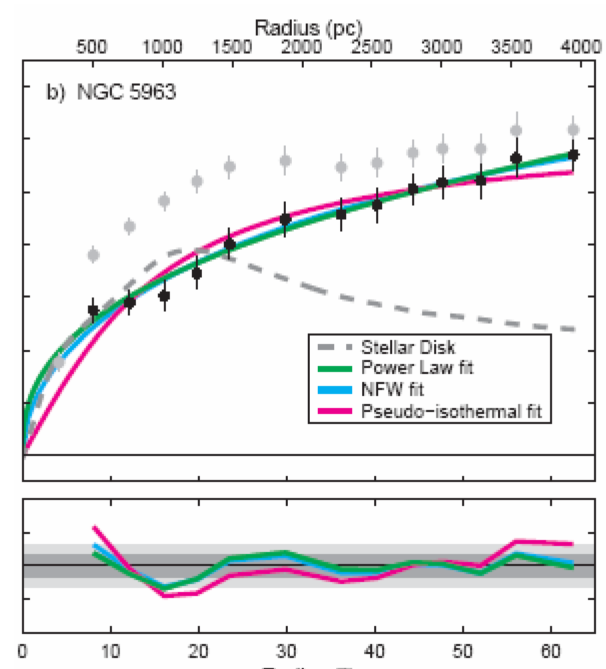
- Navarro, Frenk & White profile:

  $\rho(r) = \rho_0 \, r_s^3 / [r \, (r + r_s)^2]$

  This profile comes from cosmological simulations of formation of dark halos.

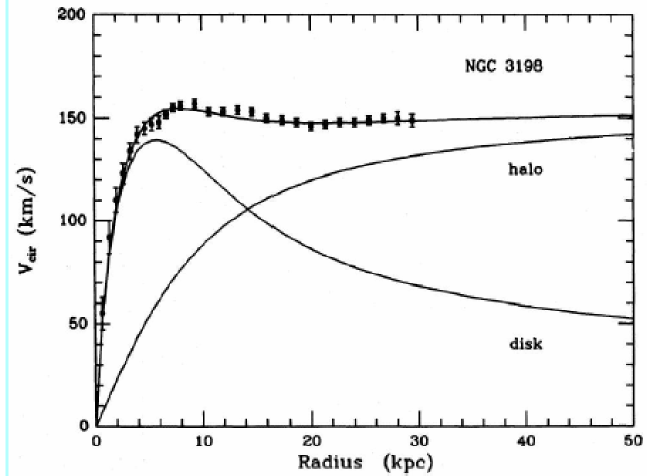
- power-law: $\rho(r) = \rho_0 \, (r_0/r)^\alpha$

- In the first two cases, the total mass is infinite (diverges with radius linearly or in the log).



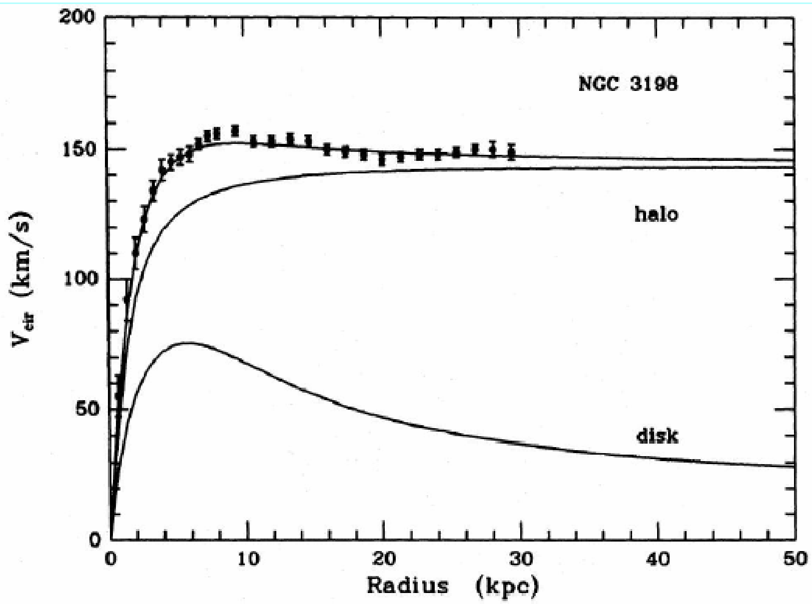
Uncertainties and degeneracies. II

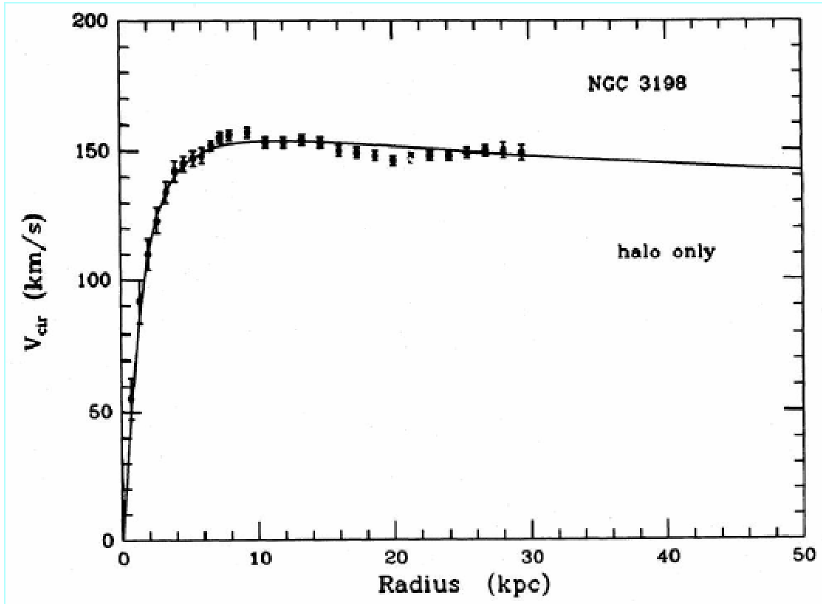
Generally the M/L used is the one that gives the maximum amplitude to disk contribution (and still consistent with observations) to the given rotation curve.



This is known as the maximum disk.

The model dark halo can be changed to have a minimum disk (left), or no disk at all (right)





Scaling relations: Tully-Fisher

Relation between the luminosity of spiral galaxies and their peak circular velocity:

$$\frac{L_H}{3\times10^{10}L_{sun}} = \left(\frac{V_{\max}}{196km/s}\right)^{3.8}$$

More luminous galaxies rotate faster.

Such a relation can be easily understood:

- The circular velocity and mass are related through: $M \sim V_{max}^2 R_d$
- The total luminosity $L = 2\pi I(0)R^2_d$.
- Assume that M/L and I(0) are constant, then $L \sim V_{max}^4$

$$\mathrm{L} \propto V^4_{\max}$$

This is one of the relations used in the distance ladder