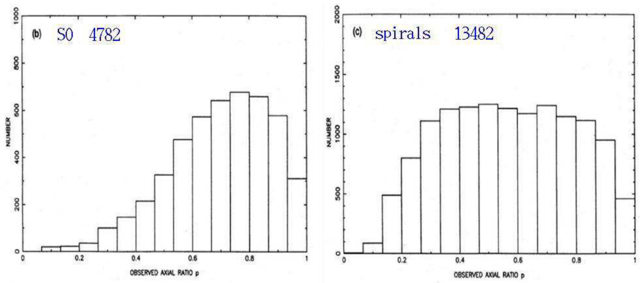
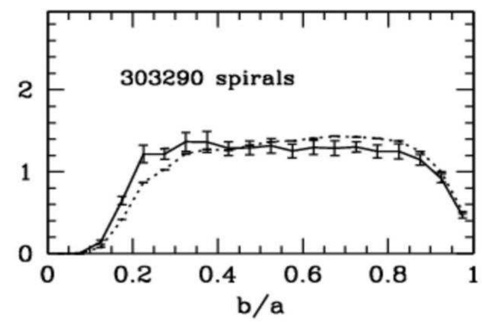


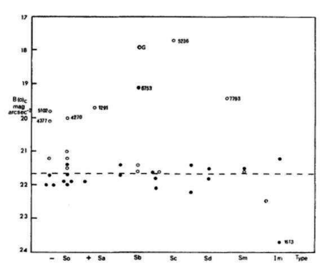
Lambas et al. (1992): distributions of the apparent axial ratios of the APM galaxies (S0 and spirals). Two distributions are very different. If we hypothesize that spirals are axisymmetric oblate bodies, then it follows that the distribution of true axial ratios is sharply peaked around $b/a \approx 0.2$. S0: b/a widely distributed from 0.25 to 0.85.



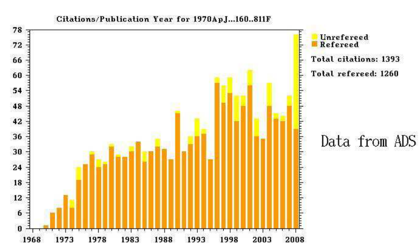
Distribution of axial ratios of spiral galaxies from the SDSS survey (Padilla & Strauss 2008).
Spirals: flat disks with $b/a = 0.21 \pm 0.02$, face-on ellipticity $e \approx 0.1$.

K. Freeman (1970) noted that the central surface brightnesses of disk galaxies clustered around $\mu_0(B) = 21.65$ ($\sigma = 0.30$!).

(Often called Freeman's law)

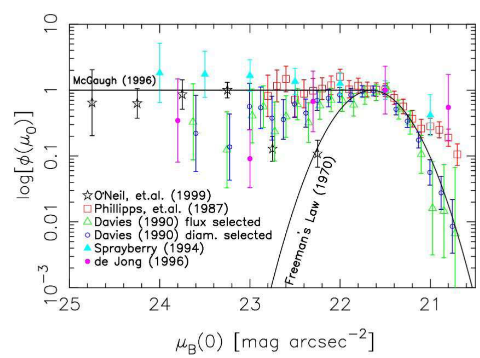


One of the most cited papers in astronomy. About 1400 citations by december 2008!



"Freeman's law" was critically discussed, for example with regard to its possible dependence on selection effects.

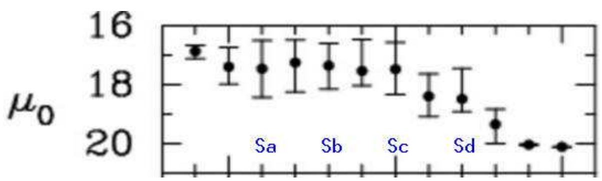
True distribution: flat space density of galaxies as a function of $\mu_0(B)$ from the Freeman value (21.65) to the survey limit of 25.



O'Neil & Bothun (2000)

The luminosity density of disk galaxies in the local Universe is dominated by high surface brightness galaxies. The contribution of LSB galaxies is $\sim 10\% - 30\%$.

Graham & Worley (2008) (K-band):

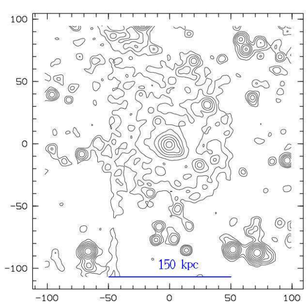


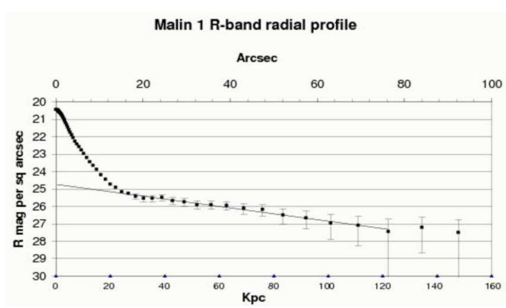
Nomenclature (McGaugh 1996):

Name	μ_0 B mag arcsec^{-2}	Σ_0 $L_\odot$pc^{-2}
VHSB	< 21.25	> 200
HSB[a]	21.25 — 22.0	100 — 200
ISB	22.0 — 22.75	50 — 100
LSB	> 22.75[b]	< 50
VLSB	24.5 — 27.0	1 — 10
ELSB[c]	> 27.0	< 1

[a]Satisfies Freeman's law.
[b]Brightness of darkest night sky.
[c]Practically invisible.

Extreme example of LSB: Malin 1 galaxy (Bothun et al. 1987).

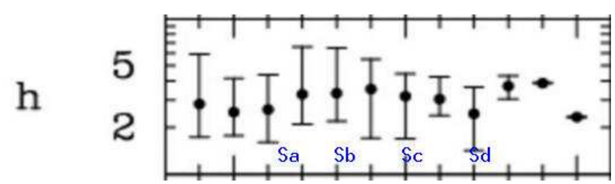




Contour map and profile from Moore & Parker (2007) – 63 co-added films in the R band.

$\mu_0(B) \approx 26^m/\square''$, $h \approx 50$ kpc !

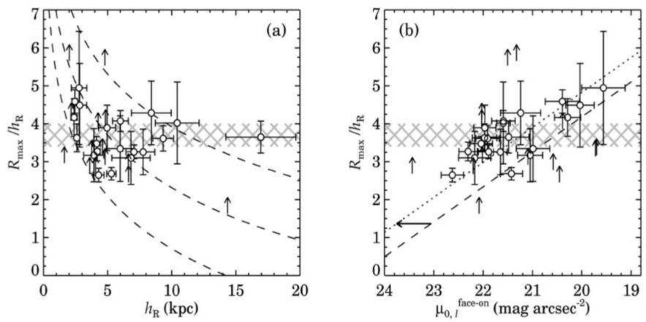
- h almost independent on the morphological type (e.g. Graham & Worley (2008), K-band):



- h depends on the wavelength:
face-on galaxies $\langle h(B)/h(K)\rangle = 1.22 \pm 0.23$ (de Jong 1996)
edge-on galaxies $\langle h(B)/h(K)\rangle = 1.56 \pm 0.46$,
$\langle h(B)/h(I)\rangle = 1.32 \pm 0.24$ (de Grijs 1998).

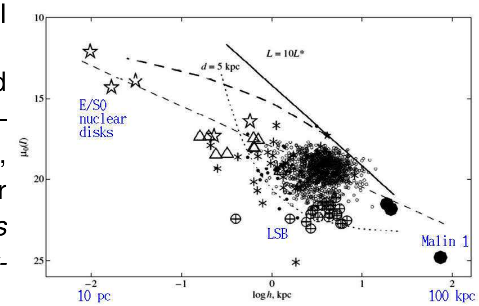
Most spiral disks are truncated at $r \sim (3-5)\,h$.

Kregel & van der Kruit (2004):



The dashed lines show the constant star-formation threshold predictions.

Distribution of the exponential disks on the $\mu_0(I)$–h plane. *Circles* – data for 1163 Sb-Sd spirals from Byun (1992), *stars* – compact nuclear disks of E/S0, *triangles* and *asterisks* – stellar disks in E/S0 galaxies, *circles with crosses* – LSB, *big filled circles* – GLSB.



The thick solid line shows the constant disk luminosity curve ($10L^*$), dotted line – the selection line for galaxies with a diameter of 5 kpc, dashed curve – the disk stability condition for the galaxies with a total luminosity of $10L^*$ (see van den Bosch 1998).
The stability condition combined with luminosity constraint ($L \le 10L^*$) determines a domain with an upper limit given approximately by the line $I_0 \propto h^{-1}$ on the μ_0–h plane (dashed line in the figure).

Interpretation of the μ_0–h plane in the framework of the CDM hierarchical scenario of galaxy formation (e.g. Mo, Mao, White 1998).
According to this scenario, non-baryonic dark halos form from primordial density fluctuations at the first stage. At the next stage, gas cools and condenses in the halos to form the disks of the galaxies.

Main assumptions of the model:
(1) the mass of the disk (M_d) is some fixed fraction of that of the halo (M) in which it is embedded – $M_d = m_d\,M$;
(2) the angular momentum of the disk (J_d) is also a fixed fraction of that of its halo – $J_d = j_d\,J$;
(3) the disk is a thin centrifugally supported structure with an exponential surface density profile – $\Sigma(r) = \Sigma_0\,e^{-r/h}$;
(4) the disks of real galaxies are stable.

One can show, neglecting self-gravitation of the disk and assuming that the halo is an isophermal sphere, that (see MMW 1998)

$$h \propto \lambda\,V_c\,\frac{j_d}{m_d}\left(\frac{H(z)}{H_0}\right)^{-1},$$

$$\Sigma_0 \propto m_d\,\lambda^{-2}\,V_c\left(\frac{m_d}{j_d}\right)^2\,\frac{H(z)}{H_0},$$

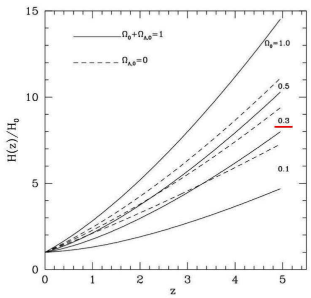
and

$$M_d \propto m_d\,V_c^3\left(\frac{H(z)}{H_0}\right)^{-1},$$

where λ is the dimensionless spin parameter defined in the standard way as λ=J $|E|^{1/2}\,G^{-1}\,M^{-5/2}$ (E is the total energy of the halo, G is the gravitational constant); V_c – circular velocity of the halo; H_0 – current value of the Hubble constant, $H(z)$ – the Hubble constant at redshift z, corresponding to the formation epoch of the dark halo.

According to the model, the disk properties are fully determined by the values of λ, $\mathrm{m_d}$, $\mathrm{j_d}$, V_c and $H(z)$. Other cosmological parameters, such as z, Ω_0, Ω_Λ, affect disks only indirectly through $H(z)$.

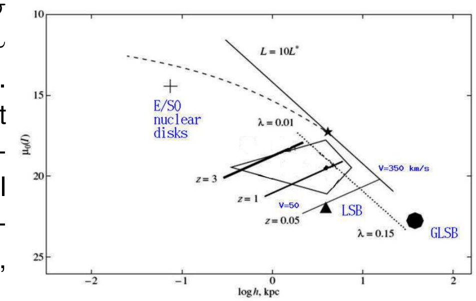
Since $H(z)$ increases with z, disks of given circular velocity are less massive, are smaller and have higher surface densities at higher redshifts. At a given z, they are larger and less compact in haloes with larger λ.



The Hubble constant (in units of its present value) as a function of z for flat and open models.

Stellar disks of real galaxies on the $\mu_0(I)$–h plane.

The quadrangle shows the $\pm 2\sigma$ box of the mean parameters of $\sim$ 1000 spirals from Byun (1992). The line segments of different thicknesses show disks loci implied by Mo et al. (1998) model ($\lambda = 0.05$, m_d=j_d=0.05) with different formation redshifts – 0.05, 1, 3.



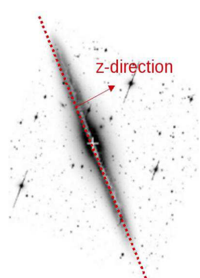
The model explains satisfactorily the position and scatter of observed disks. The data of normal spirals are consistent with formation redshift $z_f \sim 1$, LSB – $z_f < 1$.
The model predicts evolution of the μ_0 and galaxy sizes with z.

Disks are puffed up by vertical motions of stars.

Observations of edge-on disks (and MW stars) show the luminosity density can be approximated by exponential (h_z – scale height) or $\mathrm{sech}^2(z/z_0)$ laws ($z_0 = 2h_z$ at $z >> z_0$).

Scale height found to be constant with radius (?).

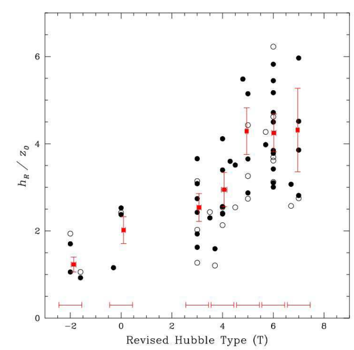
Scale height varies strongly with stellar type:
$z_0 \sim 100$ pc for young stars,
$z_0 \sim 400$ pc for older stars.



In addition to the main disk, there is evidence for a thick disk in some galaxies (including our own) with $z_0 \approx 1$ kpc.

Typical values of normalized thickness: $h/z_0 \approx 4 - 5$.

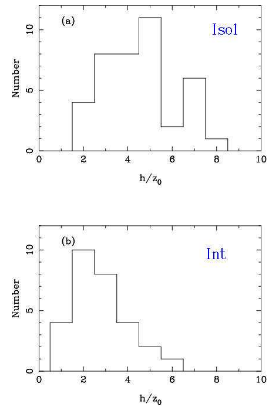
h/z_0 depends on morphological type, absolute luminosity, color, HI content:
stellar disks of late-type, blue, HI-rich and faint spirals are, on average, more thin.



Dependence of the h/z_0 ratio on galaxy type (I band – filled dots, K band – open circles) – de Grijs (1998).

There is an evidence of moderate (1.5–2 times) thickening of galactic disks in interacting systems:
the h/z_0 ratio is smaller than in isolated galaxies.

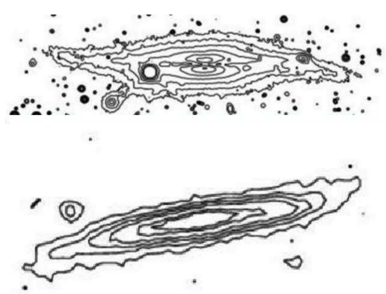
This corresponds quite well to the predictions of N-body simulations – galaxy interactions and minor mergers lead to vertical heating of stellar disks (e.g. Quinn et al. 1993).



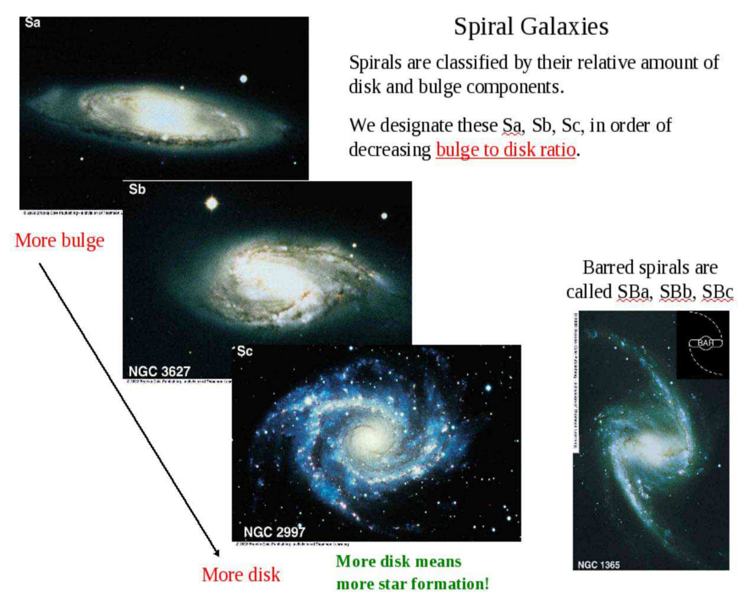
The light distribution in the disks of many galaxies is non-axisymmetric or "lopsided" with a spatial extent much larger along one half of a galaxy than the other. Near-IR observations show that lopsidedness is common.
The stellar disks in nearly 30% of galaxies have significant lopsidedness of $>10\%$ measured as the Fourier amplitude of the $m = 1$ component normalized to the average value.

The origin of lopsidedness could be due to the disk response to a tidally distorted halo, or via gas accretion.

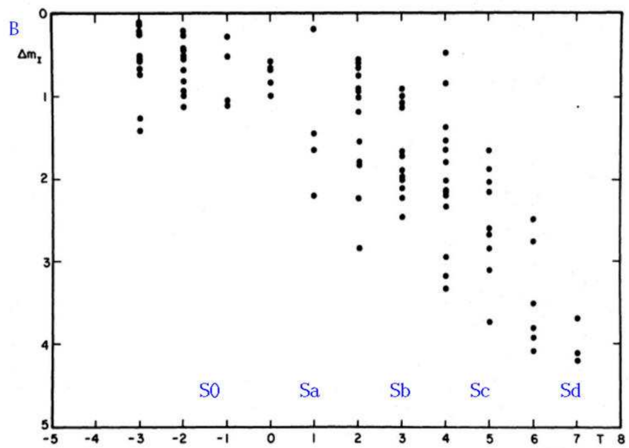
Many edge-on disk galaxies show integral-sign warps, where the majority of the disk is planar but where the outer region of the disk lies above the plane on one side of the galaxy and below the plane on the other. Most extended HI disks appear warped and at least half of all disk galaxies have optical warps. Origin of warps is still not fully understood.



There is a strong positive correlation of observed warps frequency with environment, suggesting that tidal interactions and external accretion have a large influence in creating or re-enforcing warped deformations.



Fractional luminosity of bulge expressed as magnitude difference between spheroid and galaxy as a whole (Simien & de Vaucouleurs 1986):



Disks vs. Bulges

Disks:

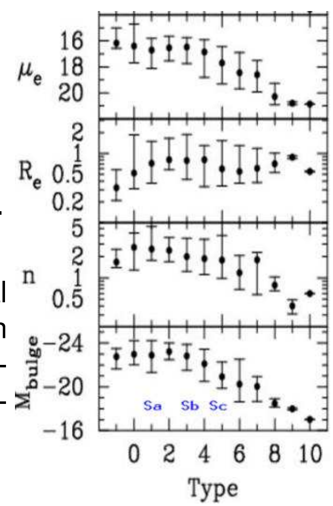
- flattened systems that rotate
- orbits of stars and gas are “circular”, rotating about disk axis
- star formation is on-going; it is can be fairly constant over the age of the galaxy
- gas and dust mass fraction is roughly 10-50% of full disk
- due on-going star formation, ages of stars widely range from age of galaxy to new
- spiral arms form as sustained density waves; where majority of star formation occurs

Bulges:

- spheroidal systems with little or no rotation
- orbits of stars are randomly oriented and highly eccentric (some are radial)
- star formation complete long ago; gas consumed efficiently long ago
- ages of stars are mainly old; most as old as the galaxy
- very little to know gas; it has been converted to stars already
- overall structure is smooth- no clumpy areas like analogous to spiral arms in disks

Surface brightness distribution:
de Vaucouleurs or Sersic $r^{1/n}$ laws.

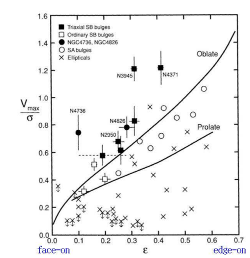
Standard approach:
bulges closely resemble elliptical galaxies. They are similar to them in terms of morphology, luminosity distribution, kinematics and stellar content.



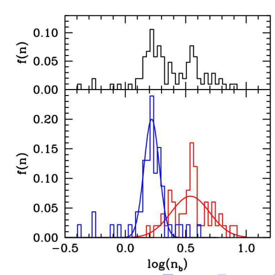
K band (Graham & Worley 2008)

Bulges are not homogeneous objects!

Kormendy (1993): “Kinematics of extragalactic bulges: evidence that some bulges are really disks”.



Fisher & Drory (2008): distribution of bulge Sersic indices *n* is bimodal, and this bimodality correlates with the morphology of the bulge.



Classical bulges

$n \geq 2$,
dynamically hot,
relatively featureless,
red colors,
same or similar fundamental plane relations as for ellipticals,
appear similar to E-type galaxies.

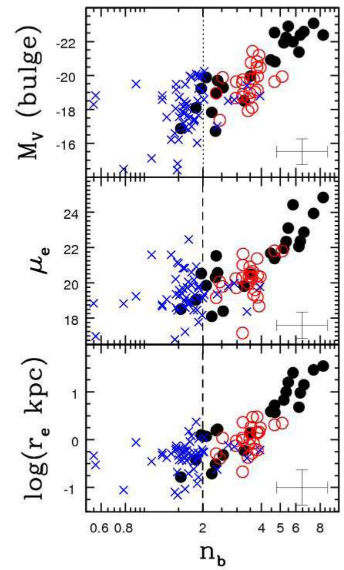
Possible origin:
hierarchical clustering via minor or major mergers.

Pseudobulges

$n \leq 2$,
kinematics dominated by rotation,
flattening similar to that of their outer disk,
nuclear bar, ring and/or nuclear spiral.

Possible origin:
secular evolution – long-term dynamical evolution (bar formation, vertical and radial transport, disk heating, new star formation, bar destruction?).

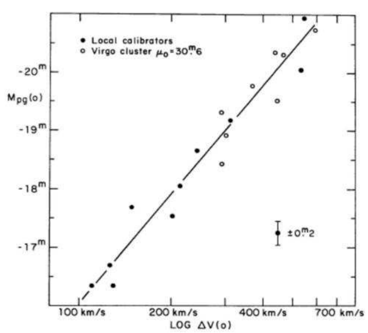
Fisher & Drory (2008):
blue crosses – pseudobulges,
red circles – classical bulges,
black circles – elliptical galaxies.



Using HI observations of spiral galaxies, in 1977 R. Brent Tully and J. Richard Fisher found that the maximum rotation velocity of spirals is closely related with their luminosity, following the relation

$$L \propto V_{max}^{\alpha},$$

where the slope of the TF relation is about $\alpha \approx 3 - 4$.

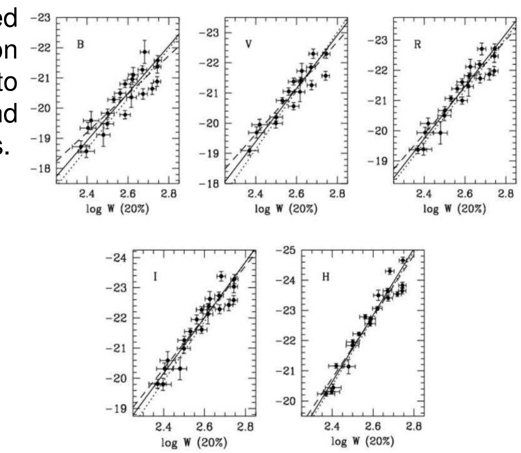


Because of this close correlation, the luminosity of spirals can be estimated quite precisely by measuring the rotational velocity. By comparing the luminosity, as determined from the TF relation, with the measured flux one can estimate the distance – without the Hubble relation!

The slope of the TF relation depends on the wavelength: the value of α increases with λ.

Sakai et al. (2000) presented the calibration of the TF relation based on Cepheid distances to 21 galaxies within 25 Mpc and 23 clusters within 10 000 km/s.
Results:
intrinsic dispersion $\approx 0.^m2$,
slopes –

$\alpha(B) = 3.2$,
$\alpha(V) = 3.5$,
$\alpha(R) = 3.5$,
$\alpha(I) = 3.7$,
$\alpha(H) = 4.4$.



Explaining the Tully-Fisher relation

The TFR is a combination of at least two independent relations:
(1) a relation between the amount of luminous matter M_{lum} and the circular velocity V_c,
(2) a relation between the luminosity and M_{lum}.

For a galaxy in equilibrium

$$V^2 = \gamma \frac{G\mathrm{M}}{R},$$

where V is representative velocity (e.g. maximum rotation velocity), M is the total mass of a galaxy, R is the characteristic radius (e.g. optical radius), G is the gravitational constant, and γ is a structural parameter depending on the shape of the mass distribution.

The total mass can be expressed as $\mathrm{M}=\mathrm{M}_{lum}+\mathrm{M}_{dark}$. Let introduce the dark matter fraction parameter $\alpha = \mathrm{M}_{dark}/\mathrm{M}_{lum}$ and the surface density parameter $\Sigma = \mathrm{M}_{lum}/R^2$.
Then

$$\mathrm{M}_{lum} = V^4 \left[\gamma(1+\alpha)^2 G^2 \Sigma\right]^{-1}$$

or

$$L = V^4 \left[\gamma(1+\alpha)^2 G^2 \Sigma \frac{\mathrm{M}_{lum}}{L}\right]^{-1},$$

where L is the total luminosity.

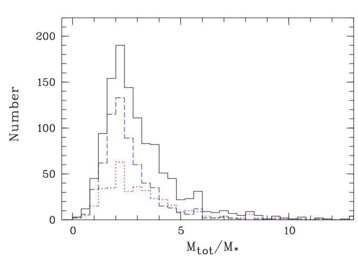
Therefore, if M_{lum}/L=const, $\mathrm{M}_{dark}/\mathrm{M}_{lum}$=const, and Σ=const (Freeman's law), we obtain $L \propto V^4$.

Are these assumptions valid?

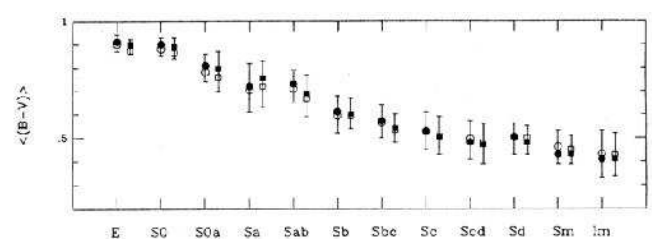
(1) M_{lum}/L=const?
Yes, in the near-infrared $\mathrm{M}_{lum}/L \approx 1$.

(2) $\mathrm{M}_{dark}/\mathrm{M}_{lum}$=const?

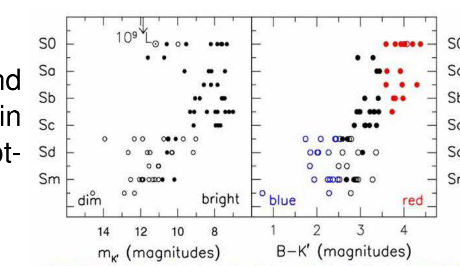
Distribution of $(\mathrm{M}_{lum}+\mathrm{M}_{dark})/\mathrm{M}_{lum}$ values for ~ 1000 galaxies from Byun (1992).
$\mathrm{M}_{lum}+\mathrm{M}_{dark} = \mathrm{R} \cdot V_{max}^2/G$, R=4$h$,
$\mathrm{M}_{lum} = L_I \cdot f_I$.
Therefore, $\mathrm{M}_{dark}/\mathrm{M}_{lum} \approx 1.5-2$.

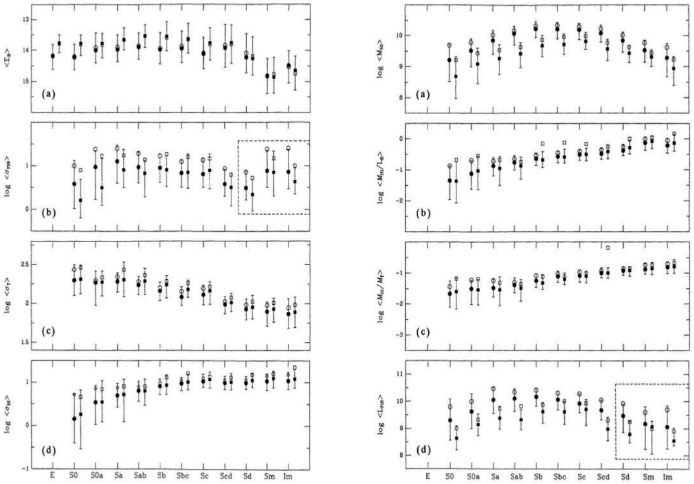


(3) But $\Sigma \neq$const – Freeman's law is not valid.
$\Sigma \cdot \mathrm{M}_{lum}/L$=const?



Apparent magnitude and $B-K'$ color of galaxies in the Ursa Major group, plotted by galaxy type.





Roberts & Haynes (1994): s.b., FIR surface density, total mass density, HI density; M(HI), M(HI)/L_B, M(HI)/M_T, L_{FIR}.