Spiral & Elliptical Galaxies I

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Physics of Galaxies 2019-2020 Q4
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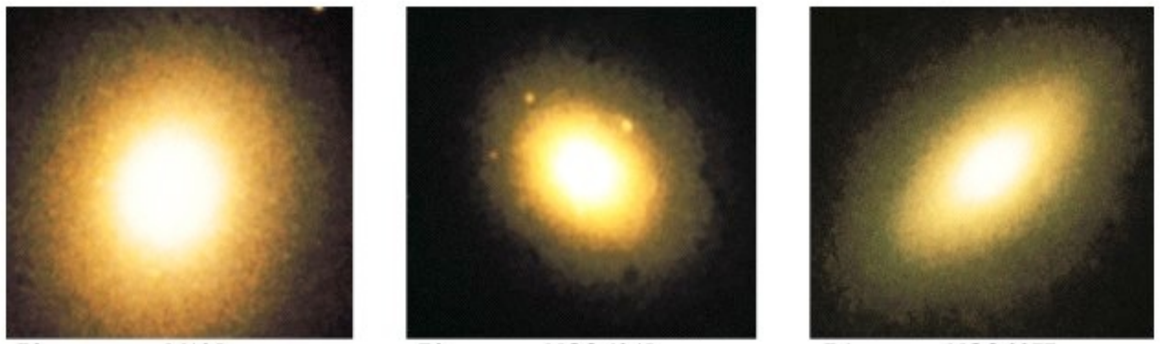
A gallery of elliptical and spirals

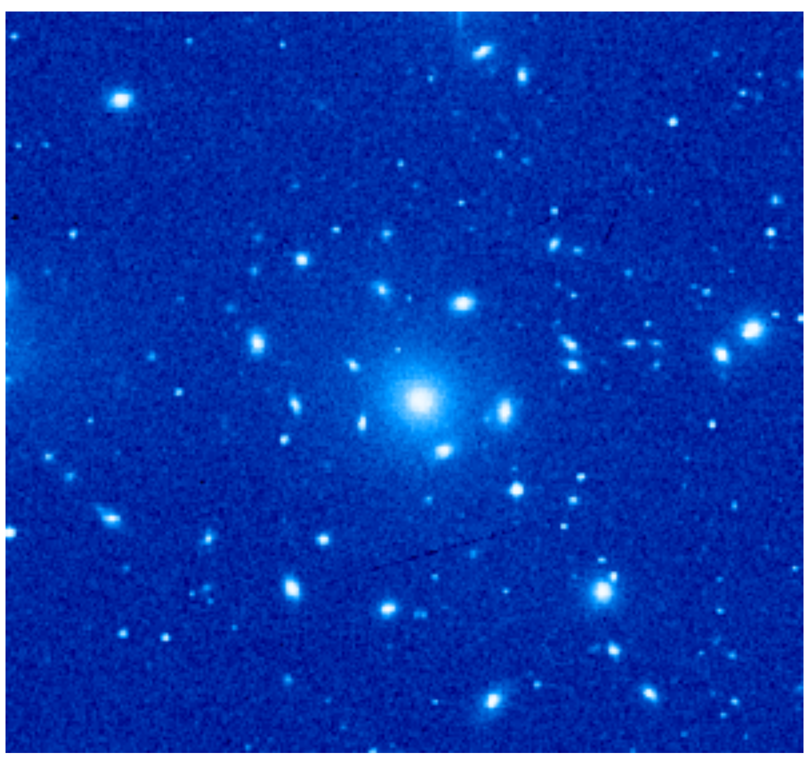
Ellipticals = early-type

the brightest and the faintest galaxies in the Universe...

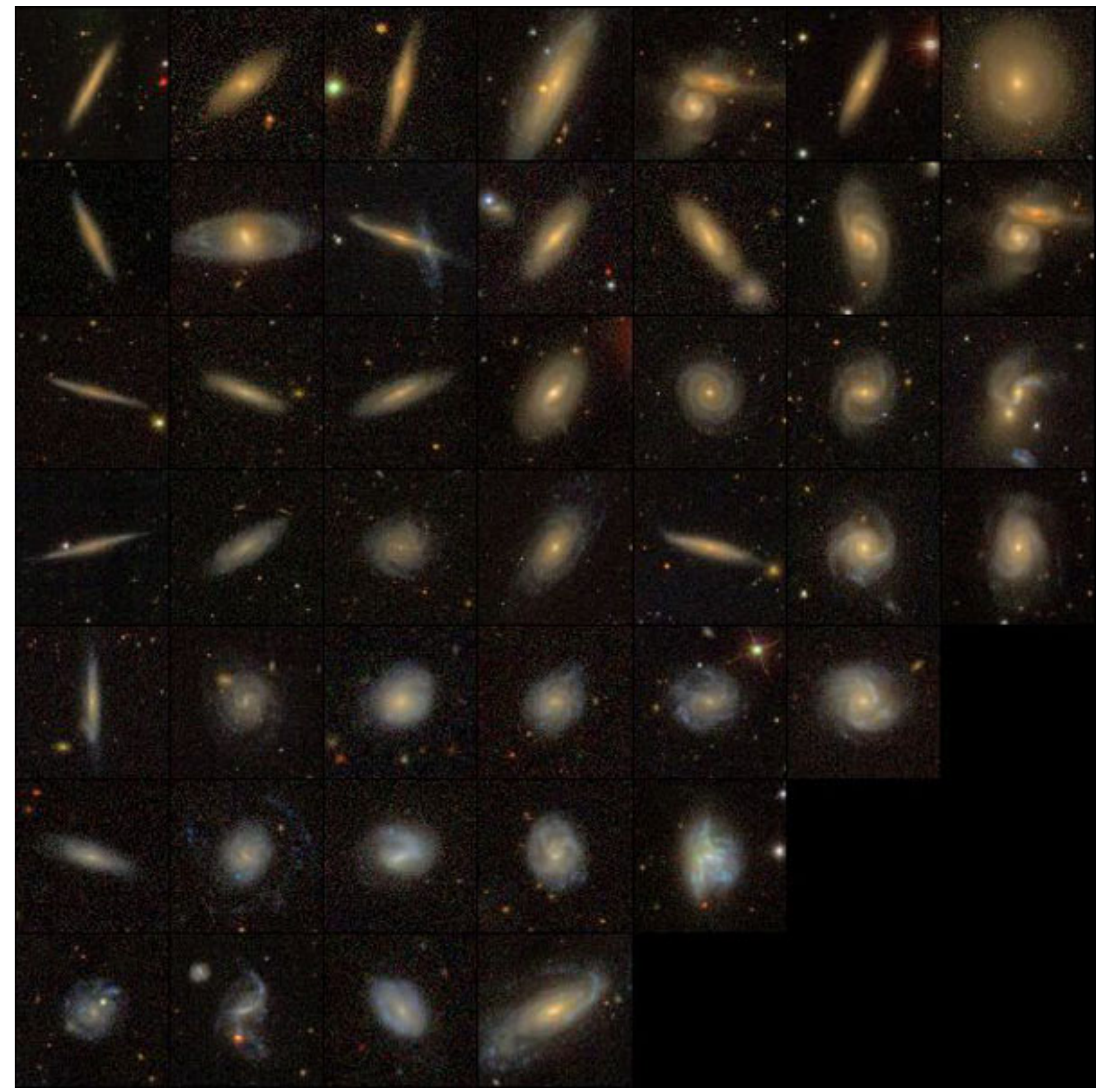


E0 M105 E3 NGC 4365 E6 NGC 3377

Coma Cluster

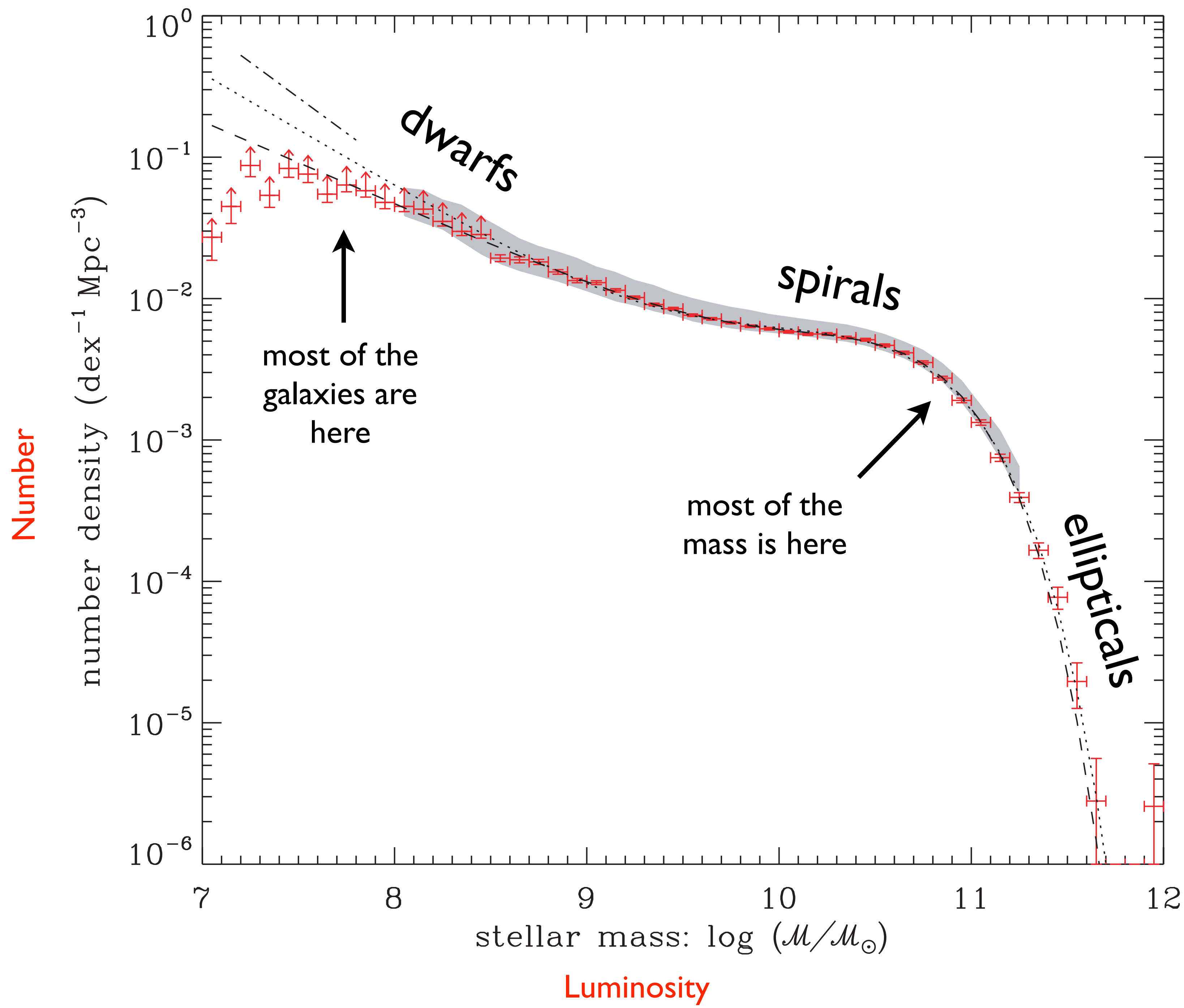


Spirals = late-type



Blanton 2009

Location on the galaxy stellar mass function



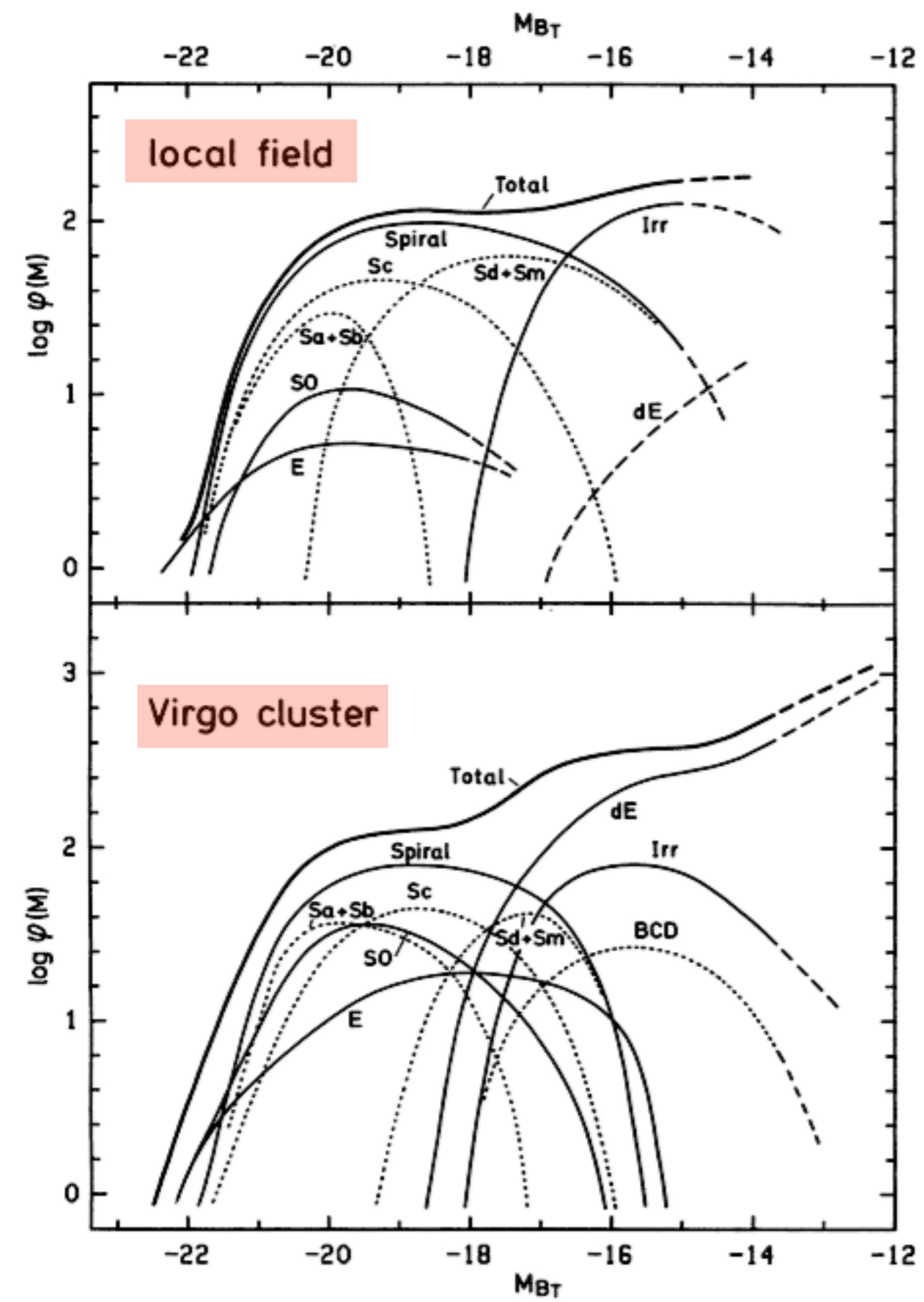
z=0

Luminosity function for galaxy type

Largest fraction in either environment of all galaxies are dwarfs (dE and Irr). Even though Sp and E the most prominent in terms of mass and luminosity.

More E in Virgo...

z=0



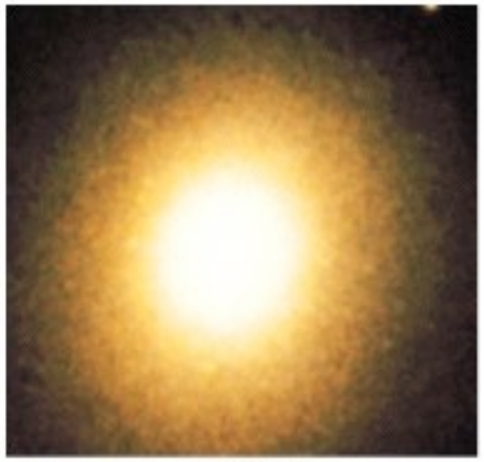
Binggeli, Sandage, Tammann ARAA (1988) ARAA ,26, 509

The total luminosity function in either environment is the sum of the individual luminosity functions of each Hubble type.

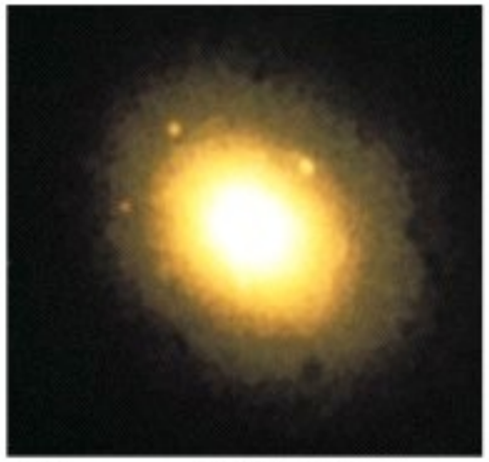
Galaxy Photometry

Morphological properties of ellipticals

the brightest and the faintest galaxies in the Universe...



E0 M105



E3 NGC 4365

E6 NGC 3377

Elliptical galaxies look very simple...

- roughly round
- smooth light distribution
- no obvious patches of star formation
- no obvious strong dust lanes (except sometimes...)

...but they're really not!

Detailed studies show significant complexity:

- large range of shapes: oblate to triaxial
- large range of luminosities and concentrations
- rotation vs. pressure support
- cuspy vs. cored centers

Morphological properties of spirals

Edge on: $i = 90^o$ Face on $i = 0^o$

Appearance depends on the distribution of stars, gas, the angle at which we see them, and even the bandpass in which we observe them

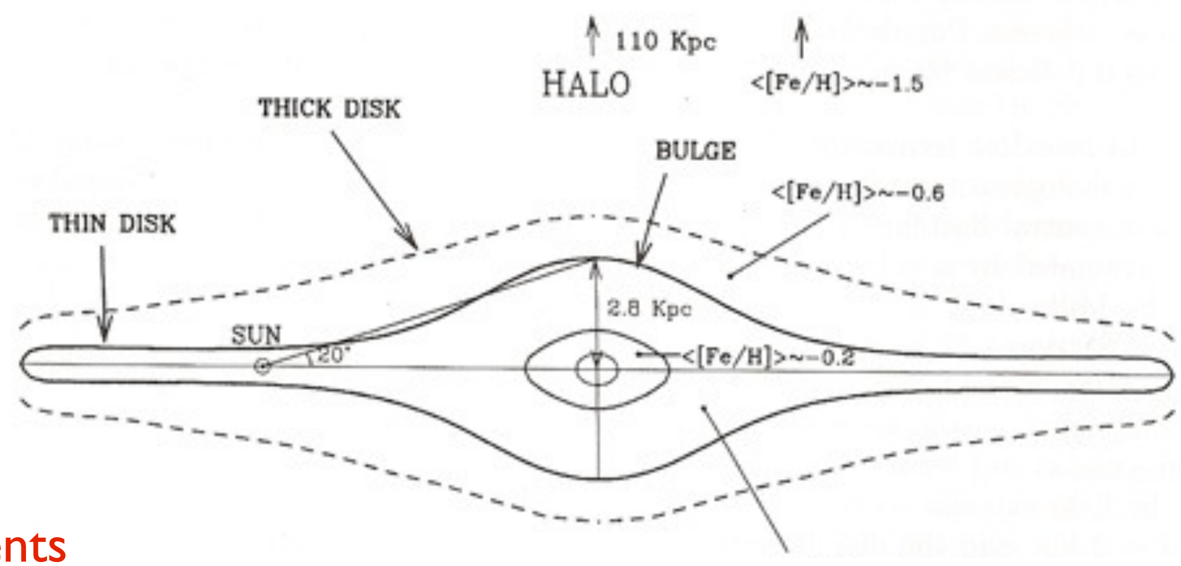
View angle determines very much the shape

- disky-like
- non-smooth structures
- dust extinction can be important
- may have bulge + disc

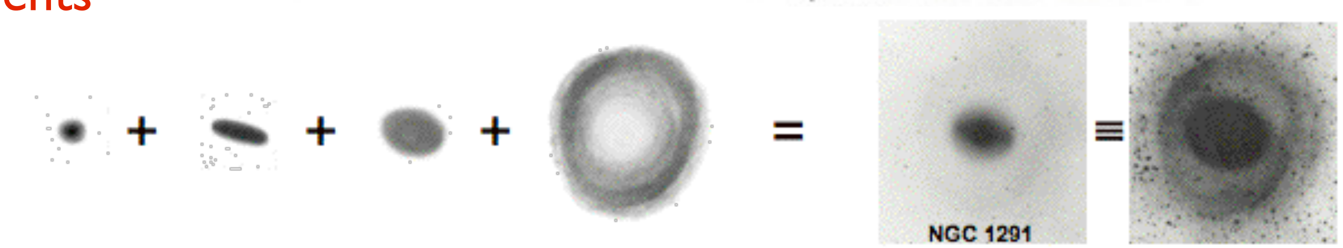
Galaxy photometry

Our classification of galaxies into different morphological types is dependent on our visual impression of their images, so understanding the distribution of their light is crucial for understanding their physics

The determination of brightness in an image is called "photometry" (measuring light), but this process also covers determination of shapes and brightness profiles



multiple components

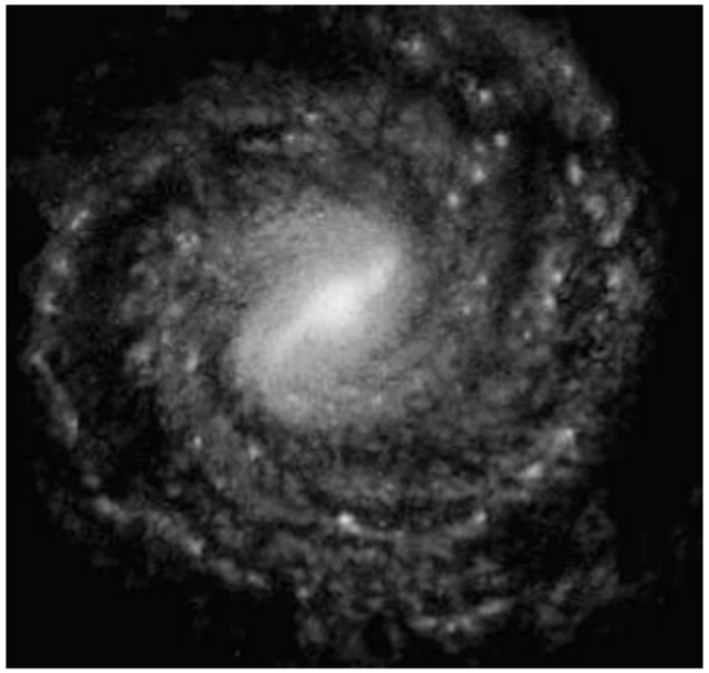


The large number of cells in classical morphology is now thought of as the many ways that components and their secondary behavior can be combined to make a galaxy.

Disc surface brightness profiles

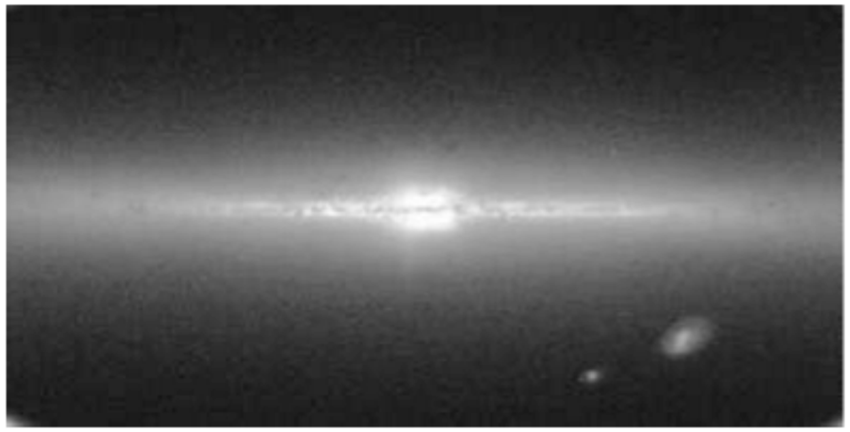
of galaxy components as a function of (R,z)

Milky Way = SBbc

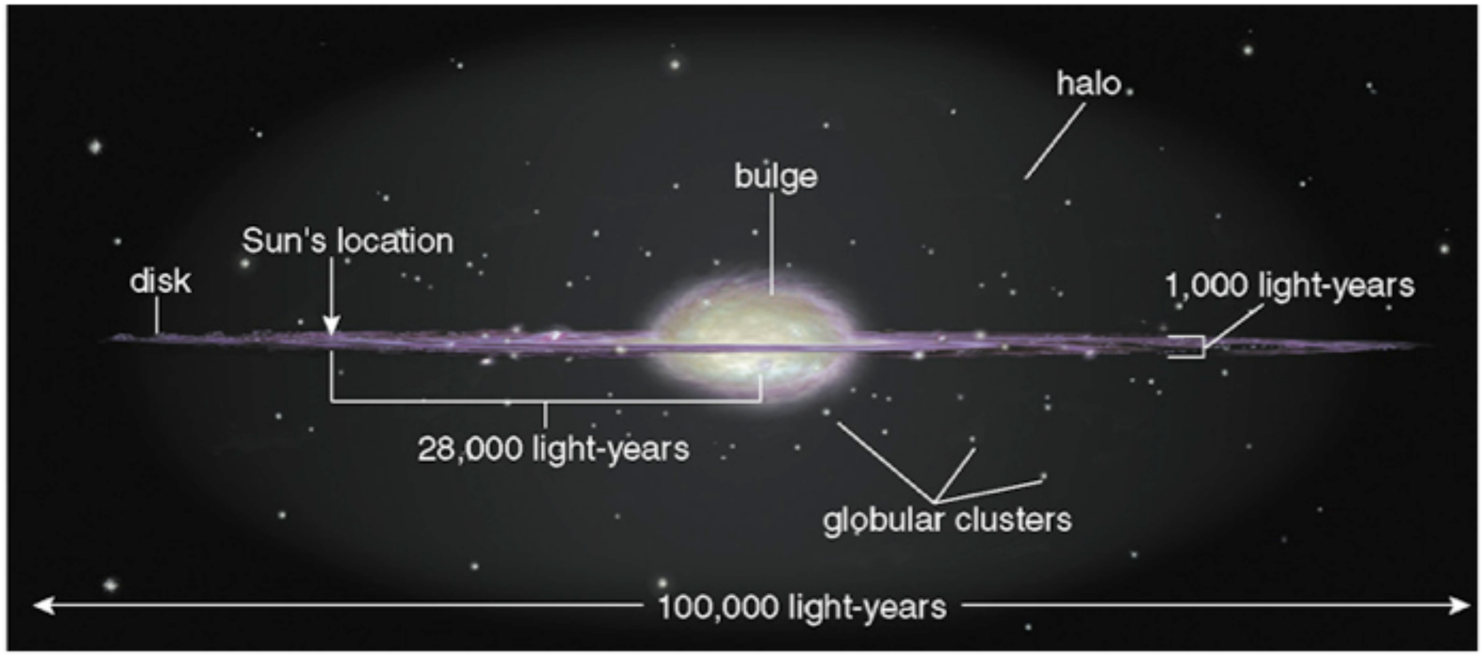


Face-on view
(Artist's conception)

Bulge, bar,
spiral arms
disk
+
(halo, DM halo)

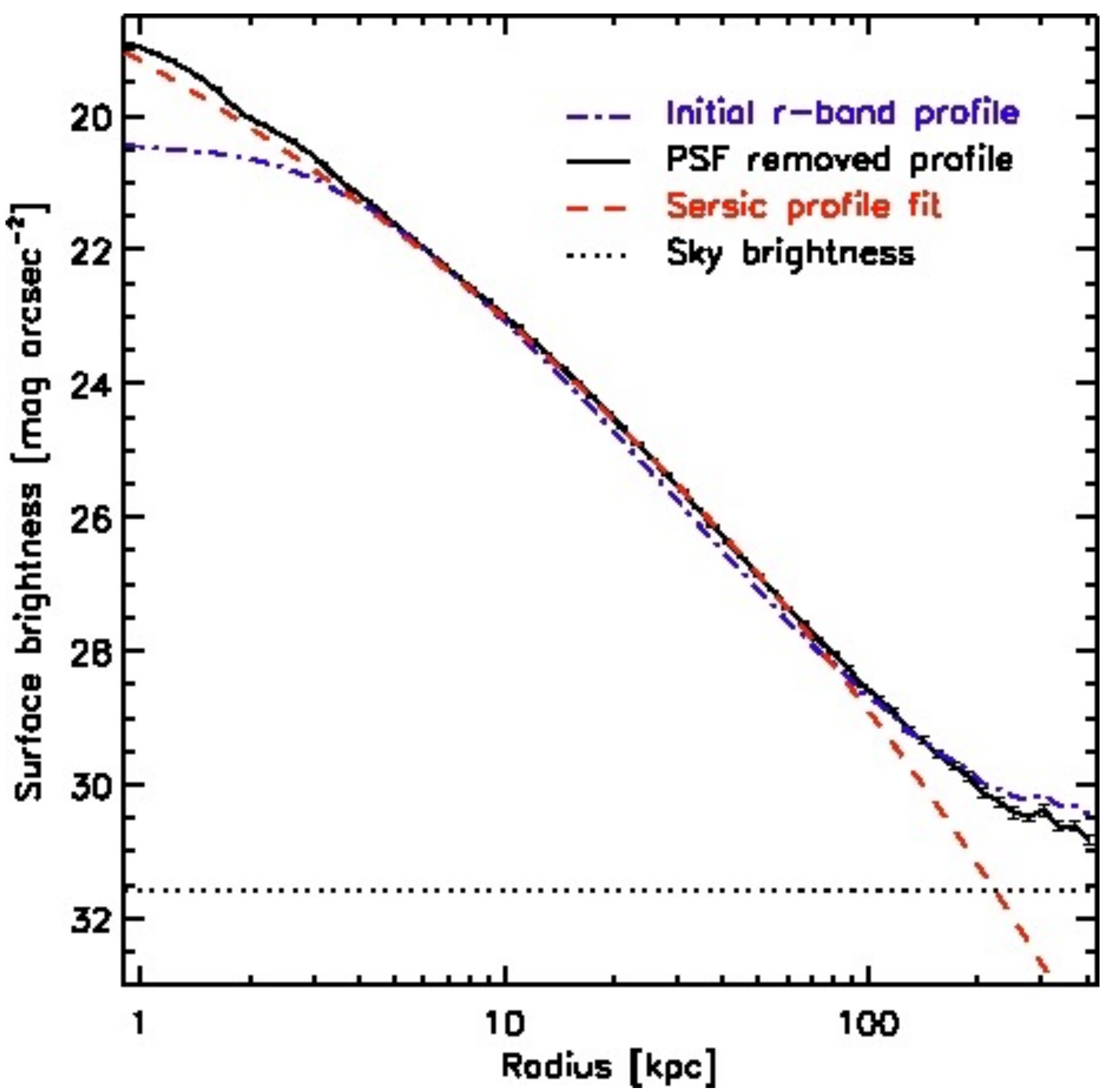


Edge-on view :
Actual infrared image
from COBE satellite



Edge-on view
(Artist's conception)

Reminder: radial light profiles



$$I(r) = I_e \, exp \left\{ -b_n \left[(r/r_e)^{1/n} - 1 \right] \right\}$$

3 free-parameter model

n = Sérsic index

n = 1 - exponential (pure disk)

n = 4 - de Vaucouleurs

Picture credit: P. Van Dokkum

Sérsic profiles

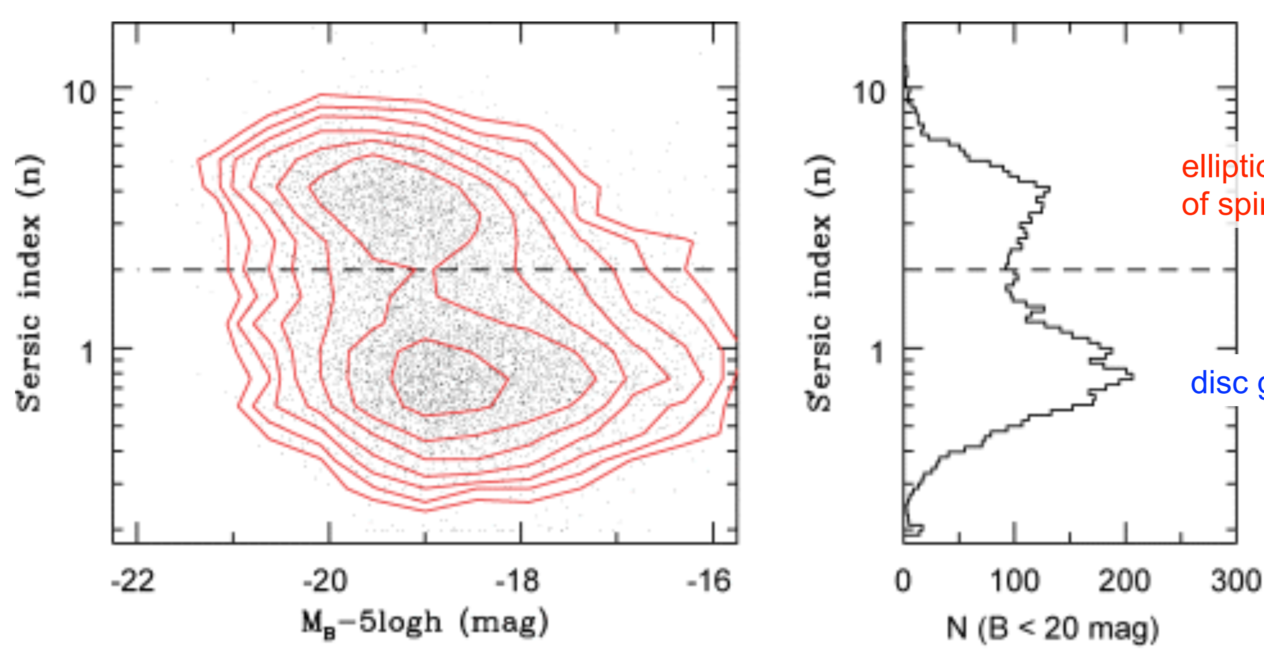
Generalised version of $r^{1/4}$ law is frequently used in which 1/4 is replaced by 1/n. Often called **Sérsic** (1968) **models** have been shown (Caon et al 1993) to be an even better fit to E's, though it increases the number of free parameters:

$$\mu(r) = \mu_e + 8.3268\left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right]$$

mag arcsec^{-2}

Where μ_e r_e and n are all free parameters used to obtain the best possible fit to the actual surface brightness profile.

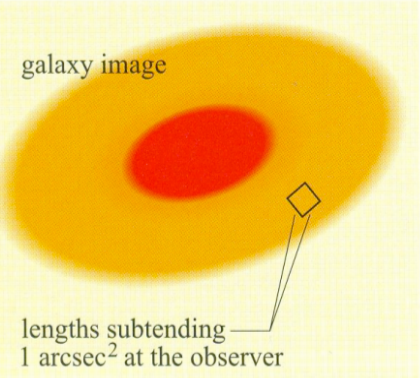
This formalism can be used to discriminate between disk-dominated and bulge-dominated galaxies. Especially suited to automated analyses of large samples.



Distribution of Sersic-n for 10 095 galaxies selected from the Millennium Galaxy Catalogue (Driver et al. 2006, MNRAS, 368, 414)

Measuring surface brightness

Surface Brightness



The surface brightness I(x) is the amount of light contained in an area at a particular point x in an image.

Consider a square area with a side of length D of a galaxy at distance d. This length will subtend an angle, $\alpha = D/d$.

If the total luminosity of the galaxy in that area is L, then the received flux is, $F=L/(4\pi d^2)$

So the surface brightness is: $I(x) = F/\alpha^2$

Surface brightness is independent of distance (d) since flux decreases as $1/d^2$, but the area subtended by 1 sq arcsec increases as d^2 (until cosmological dimming, $1/(1+z)^4$, becomes important)

Magnitude per square arcsecond is usual units of surface brightness:

$$\mu_\lambda(x) = -2.5 \log I_\lambda(x) + \text{constant}_\lambda \quad \text{(mag arcsec}^{-2}\text{)}$$

In the B-band, the constant is 27 mag/arcsec^2, which corresponds to $1\ L_\odot \mathrm{pc}^{-2}$

Thus $I_B = 10^{-0.4(\mu_B - 27)}\, L_{\odot,B} \mathrm{pc}^{-2}$

Cosmological dimming (Tolman test)

Surface brightness is flux per unit solid angle: $B = \dfrac{f}{d\omega}$

This is the same as the luminosity per unit area, at some distance D. In cosmology, $B = \dfrac{L}{D_L^2}\dfrac{D_A^2}{dl^2}$

In a stationary, Euclidean case, $D = D_L = D_A$, so the distances cancel, and $SB = const$. But in an expanding universe, $D_L = D\,(1+z)$, and $D_A = D\,/\,(1+z)$, so:

$$B = \frac{L}{dl^2}\frac{D_A^2}{D_L^2} = \frac{L}{dl^2}(1+z)^{-4}$$

Note that this is independent of cosmology!

dw= dl/D_A ~ (dl/D_A)^2 for small angles.

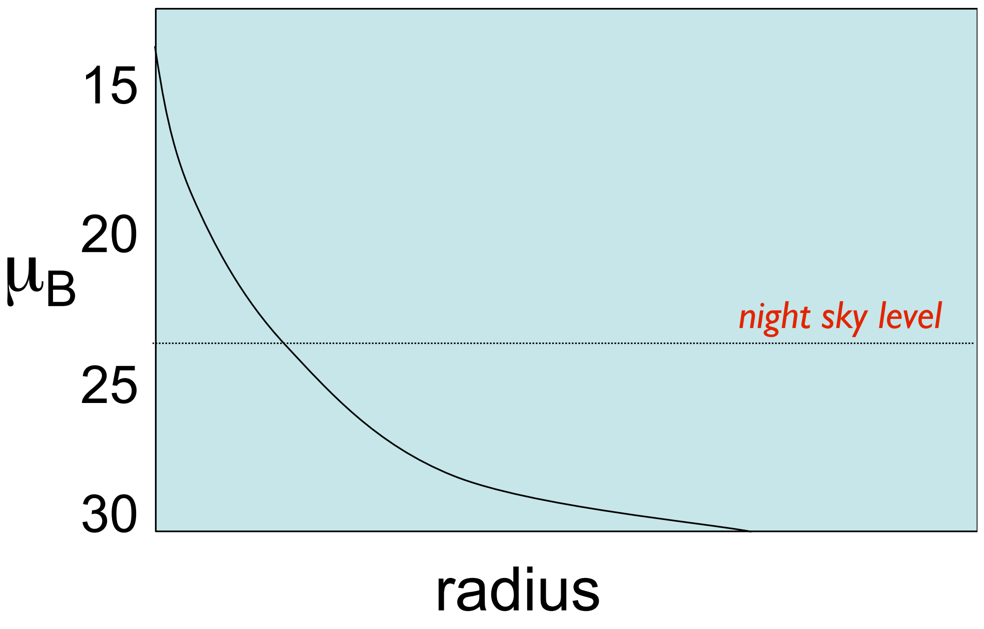
dl is the size of the object.

Surface brightness profile

NGC 7331

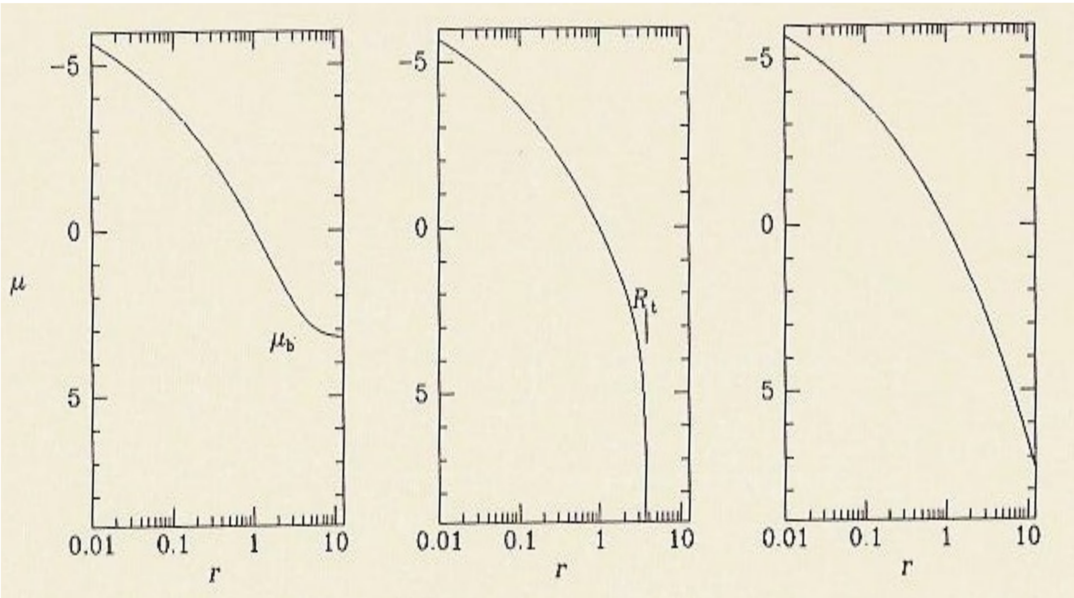
An isophote is closed curve connecting points of equal surface brightness.

A Surface brightness profile is produced by azimuthally averaging along isophotes (elliptical annuli).



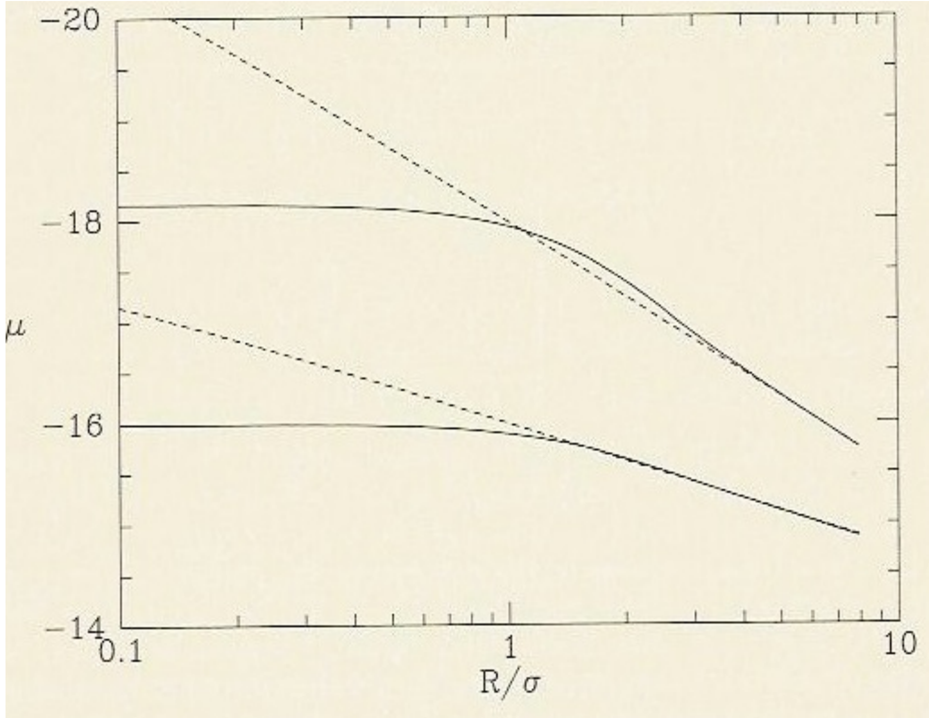
Note: the largest isophote usually represents the lowest level that can be seen above the instrumental noise (not physical boundary)

Sources of error in surface brightness



Sky Background Subtraction –
if the sky is over or under subtracted this can have a dramatic effect on the shape of the profile.

Sources include: light pollution from nearby cities, photochemical reactions in the Earth's upper atmosphere, the zodiacal light, unresolved stars in the Milky Way, and unresolved galaxies.



Seeing effects –
unresolved points are spread out due to effects of our atmosphere, quantified by the Point Spread Function (PSF) FWHM (σ) on the images

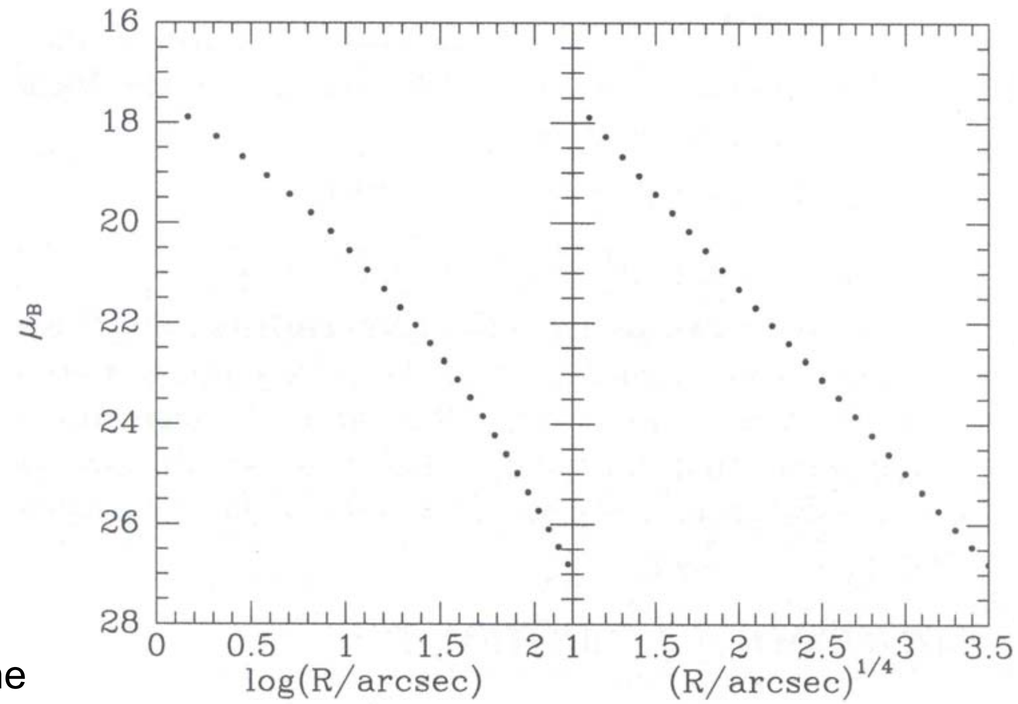
-makes central part of profile flatter
-makes isophote rounder

Surface brightness - ellipticals

Elliptical galaxies have very smooth profiles over 2 orders of magnitude in radius, usually falling off as $R^{1/4}$

Light in ellipticals is highly concentrated

NGC1700



In specifying the radius of a galaxy it is necessary to define the surface brightness of the isophote being used to determine that radius.

Effective radius, r_e, is the projected radius within which one-half of the galaxies light is emitted. This means that the surface brightness level at r_e (μ_e) depends on the distribution of surface brightness with radius.

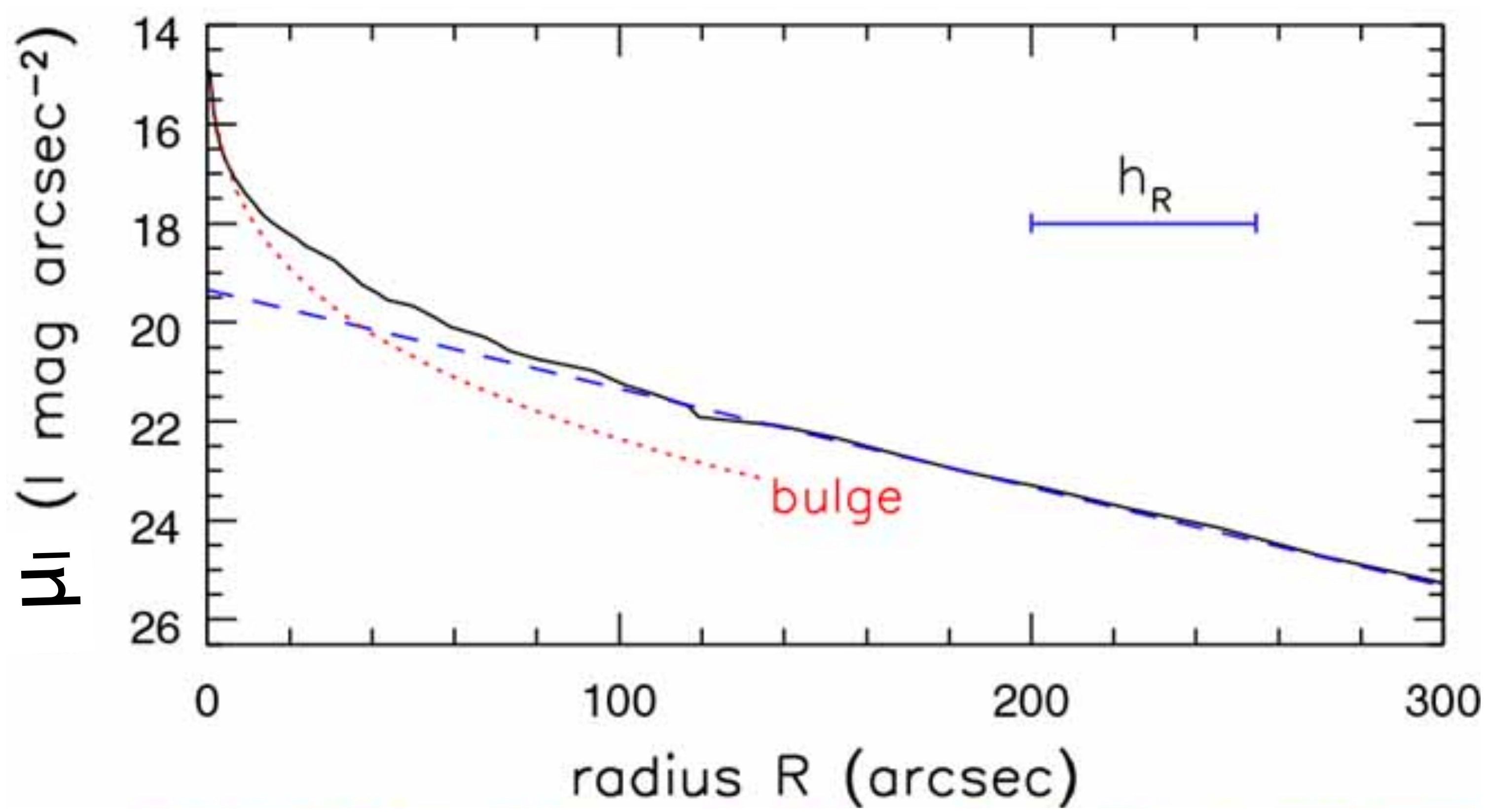
For large ellipticals, the surface brightness distribution typically follows an $r^{1/4}$ law (de Vaucouleurs profile):

$$\mu(r) = \mu_e + 8.3268\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right] \quad \text{mag arcsec}^{-2}$$

Or, in physical units:

$$\log_{10}\left[\frac{I(r)}{I_e}\right] = -3.3307\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right] \quad L_\odot\,\mathrm{pc}^{-2}$$

Surface brightness - bulge + disc



The density of stars in the disc drops by a factor of e as we move out in radius R by one scale length h_R

The effective radius R_e, the radius of a circle that includes half of the light.

The disc has an exponential profile: $I(R) = I_0 \exp(-R/h_R)$

$$\boxed{\mu(R) = \mu_0 + 1.09\left(\frac{R}{h_R}\right)}$$

The bulge follows an $r^{1/4}$ (or de Vaucouleurs) law:

$$I(R) = I_e 10^{-3.33((R/R_e)^{1/4}-1)}$$

$$\boxed{\mu(R) = \mu_e + 8.3268\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right]}$$

Surface brightness - bulge + disc (cont.)

disc galaxies are composite systems,

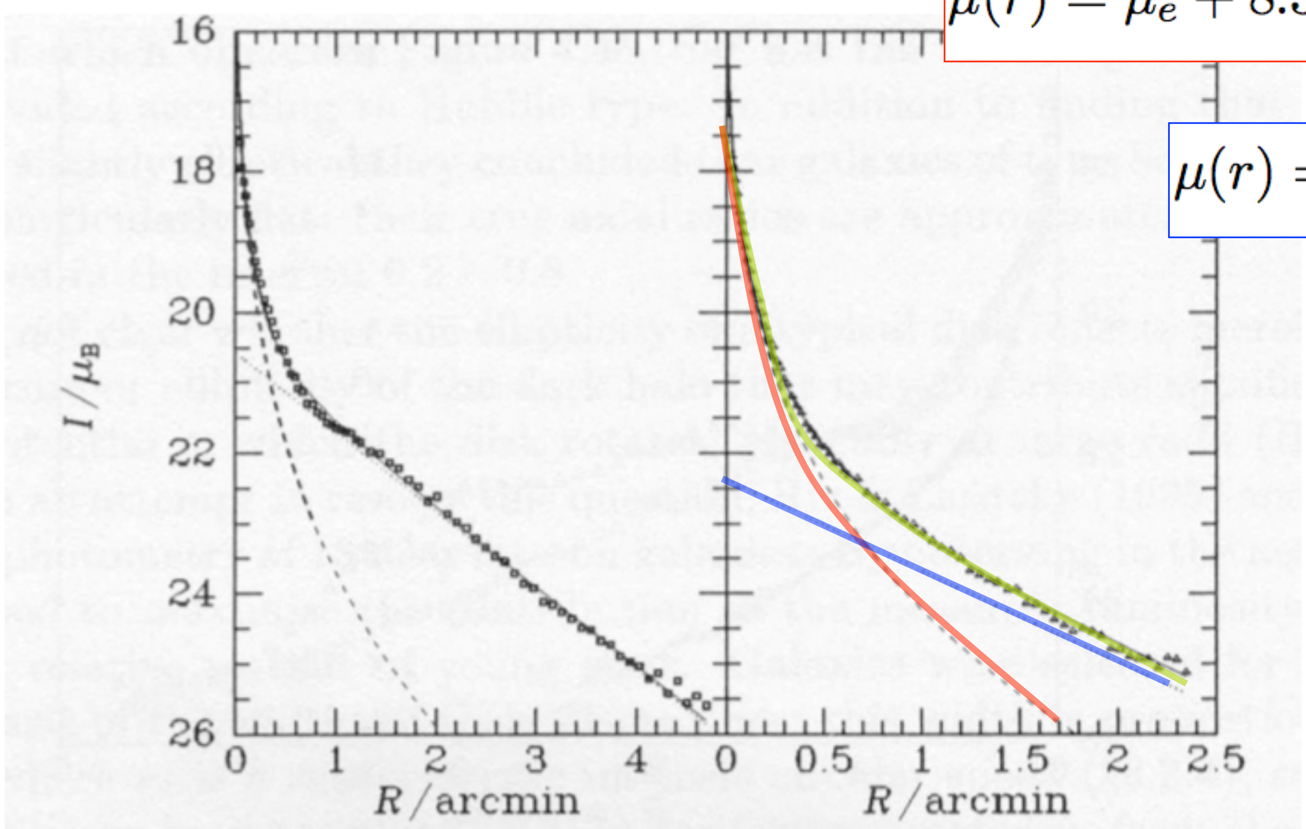
Surface Brightness profile of Spirals and S0s galaxies (Bulge + Disk) can be fitted by a (de Vaucouleurs + Exponential) profile

$$\mu(r) = \mu_e + 8.3268\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]$$

bulge

$$\mu(r) = \mu_0 + 1.09\left(\frac{r}{h_r}\right)$$

disk



Diamonds, Triangles = observed B-band surface brightness profiles of 2 spirals
Dotted curve = Exponential fits to disk
Dashed curve = De Vaucouleurs fit to bulge
Solid curve = Exp + de Vauc fit

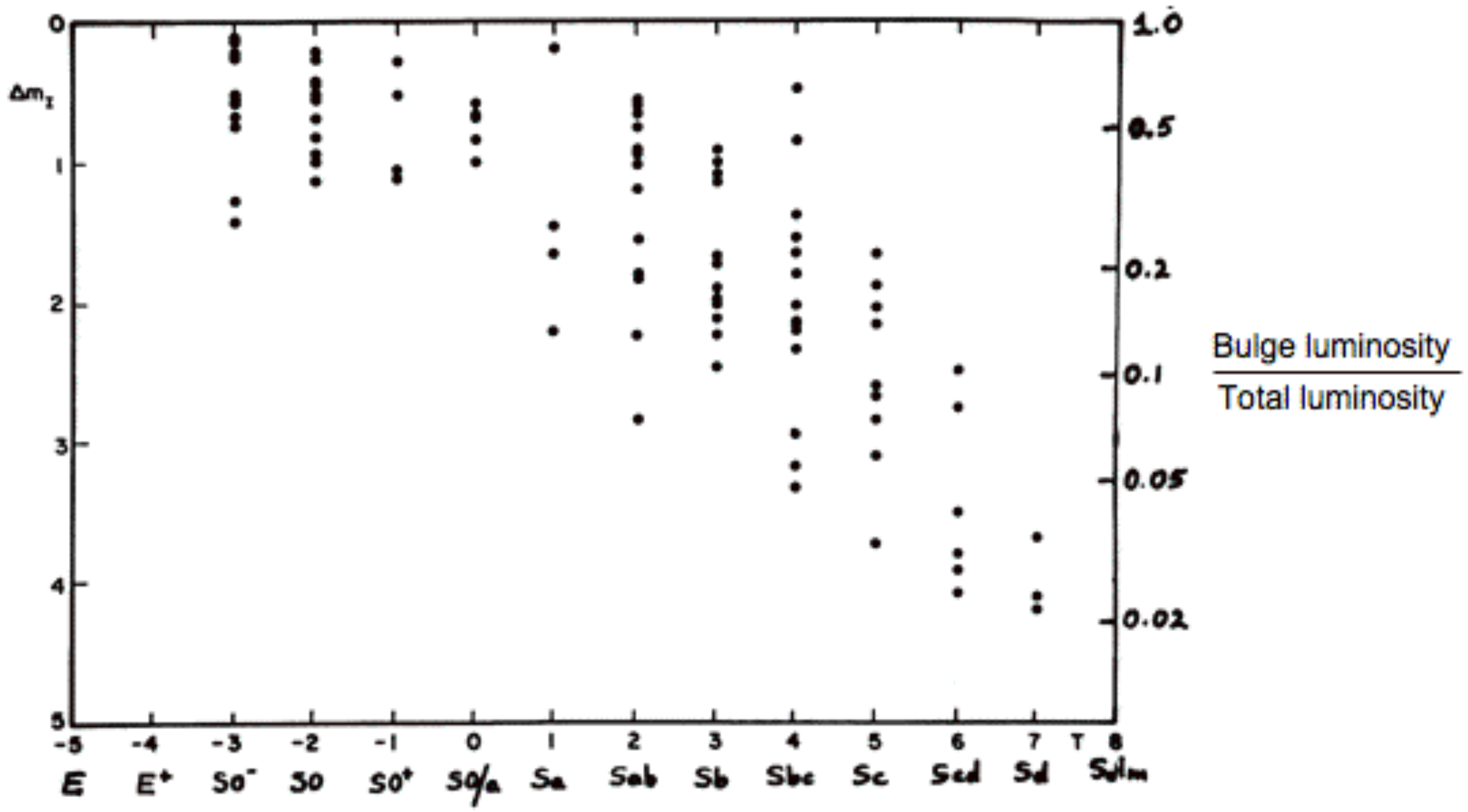
2-component

B/T per galaxy type

Bulge-to-Disc ratio

Contribution of the bulge to the total light of a galaxy

$$B/T = \frac{R_e^2 I_e}{R_e^2 I_e + 0.28 h_R^2 I_0}$$



The importance of the bulge increases moving towards earlier types

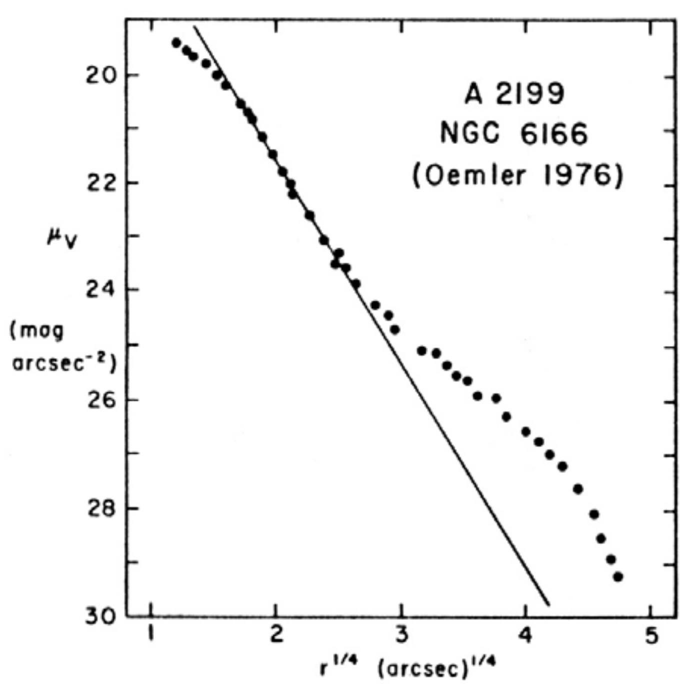
Simien & de Vaucouleurs 1986

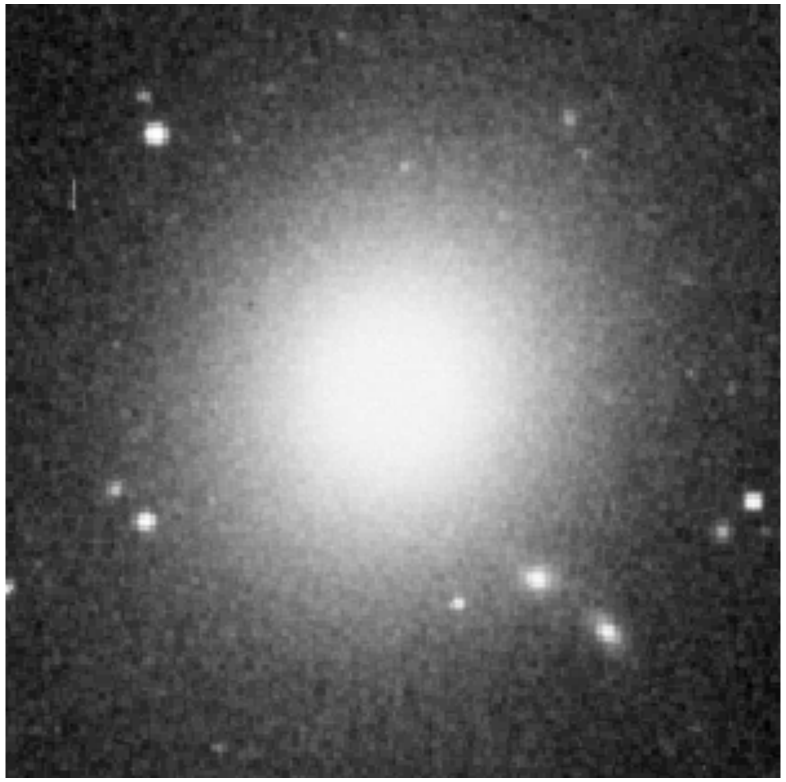
The outskirts of elliptical galaxies

•The surface brightness profile of giant ellipticals often shows an excess of light in the outer parts compared to the de Vaucouleurs profile.

•Such galaxies are known as ***cD Galaxies***. They are usually located at the center of clusters of galaxies, or in areas with a dense population of galaxies.

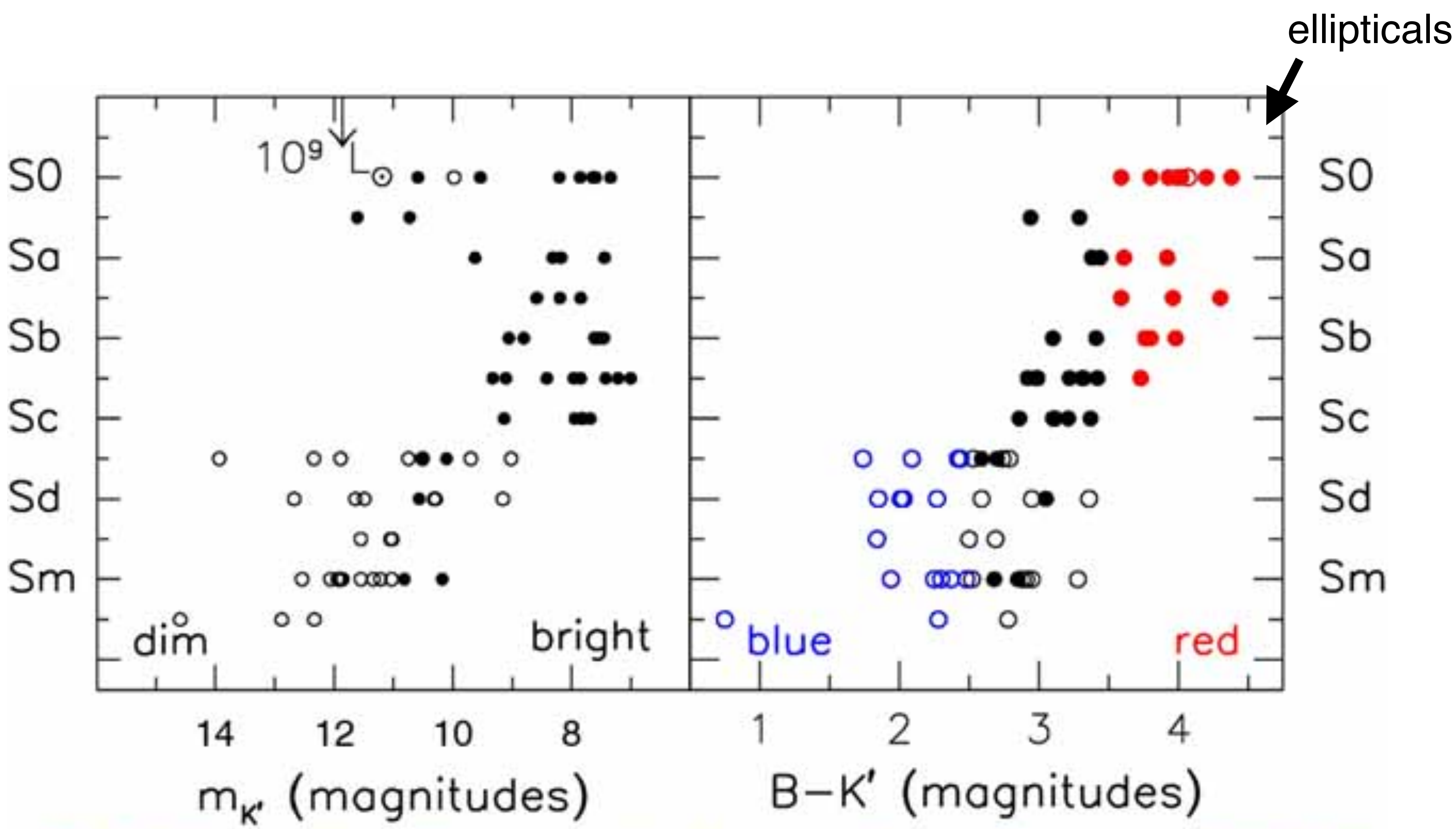
•This excess emission indicates the presence of an extended halo. The cD halos could belong to the cluster rather than to the galaxy.





M87, the central cD galaxy in the clusters of galaxies inVirgo. Note the extended, low-surface brightness halo.

Colours of ellipticals and spirals



Galaxies get bluer as the disks become more prominent (and fainter, too, because disk-dominated galaxies tend to be less massive than bulge-dominated galaxies)

Scaling Relations

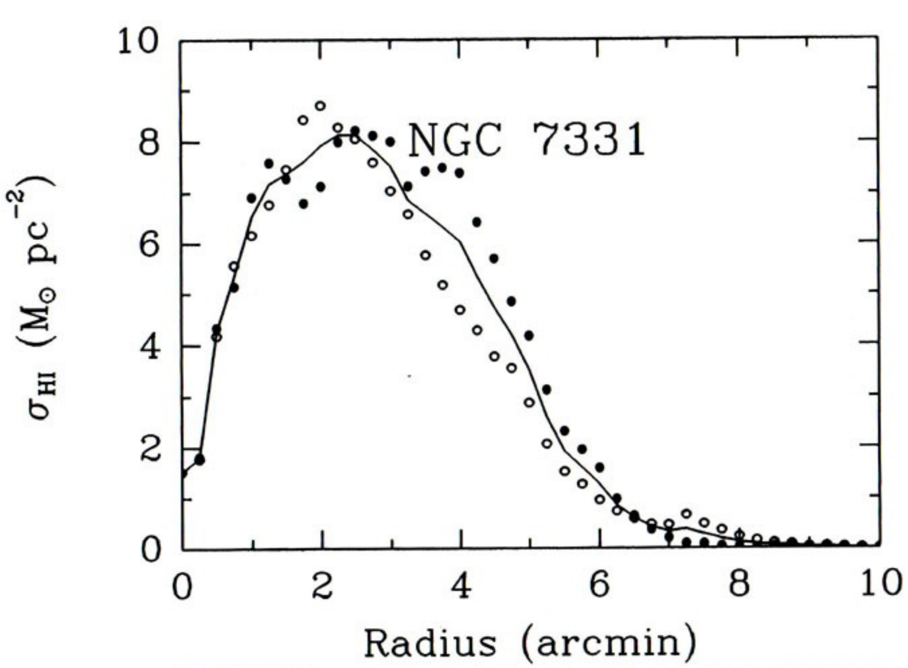
Rotational velocities in spirals from gas

In central regions, contours are parallel to the minor axis

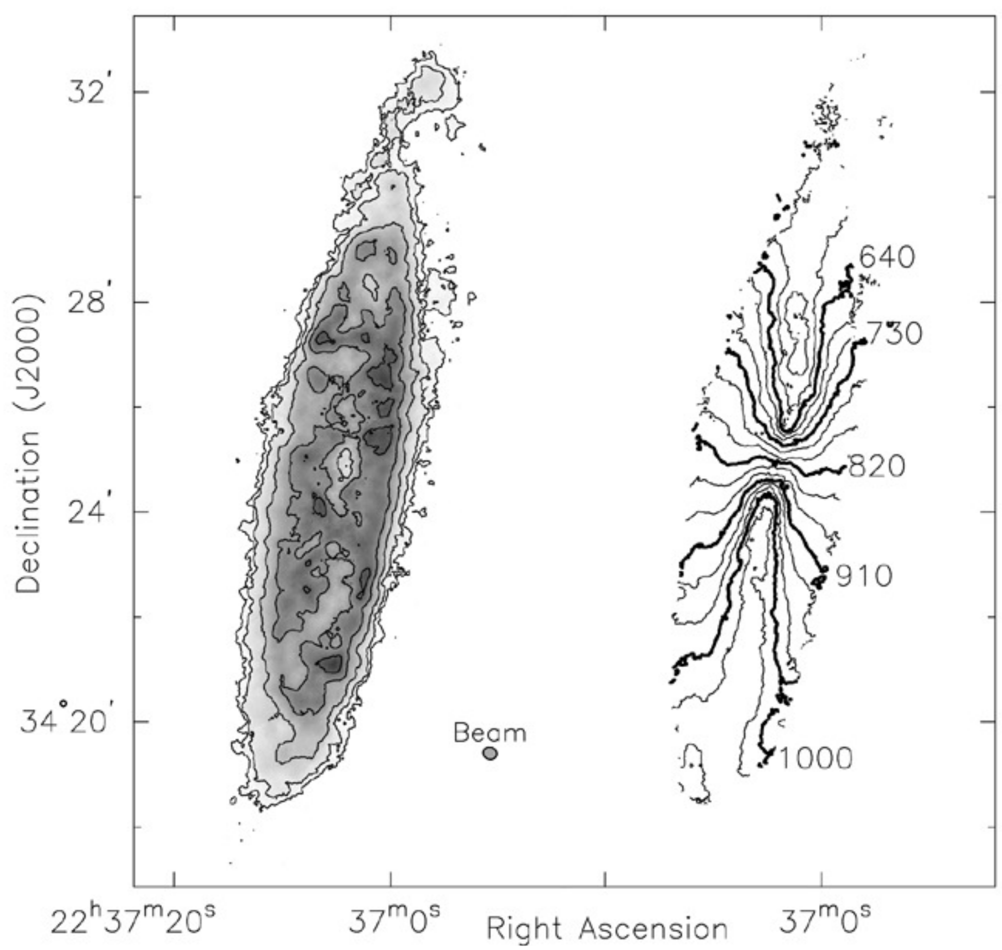
Further out, they are nearly radial

The kinematic major axis is the line connecting the points where the radial velocities deviate the most from the systemic velocity

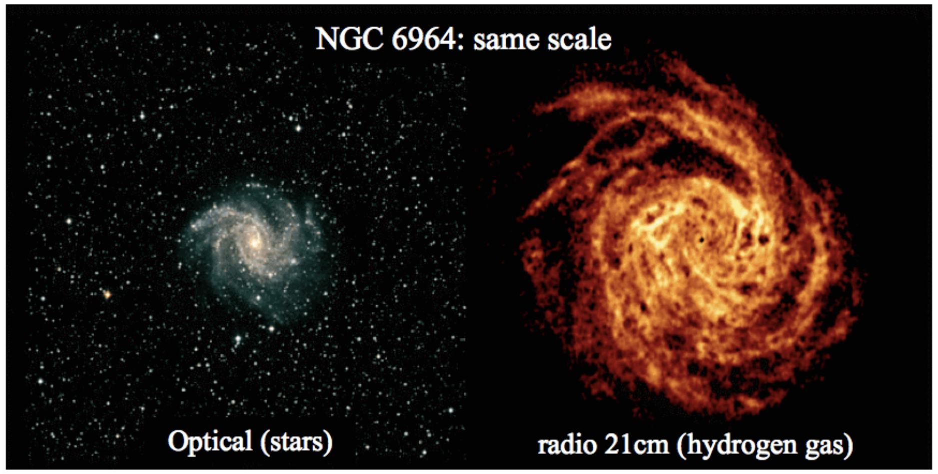
The denser the contours, the more rapid the change in V(R)



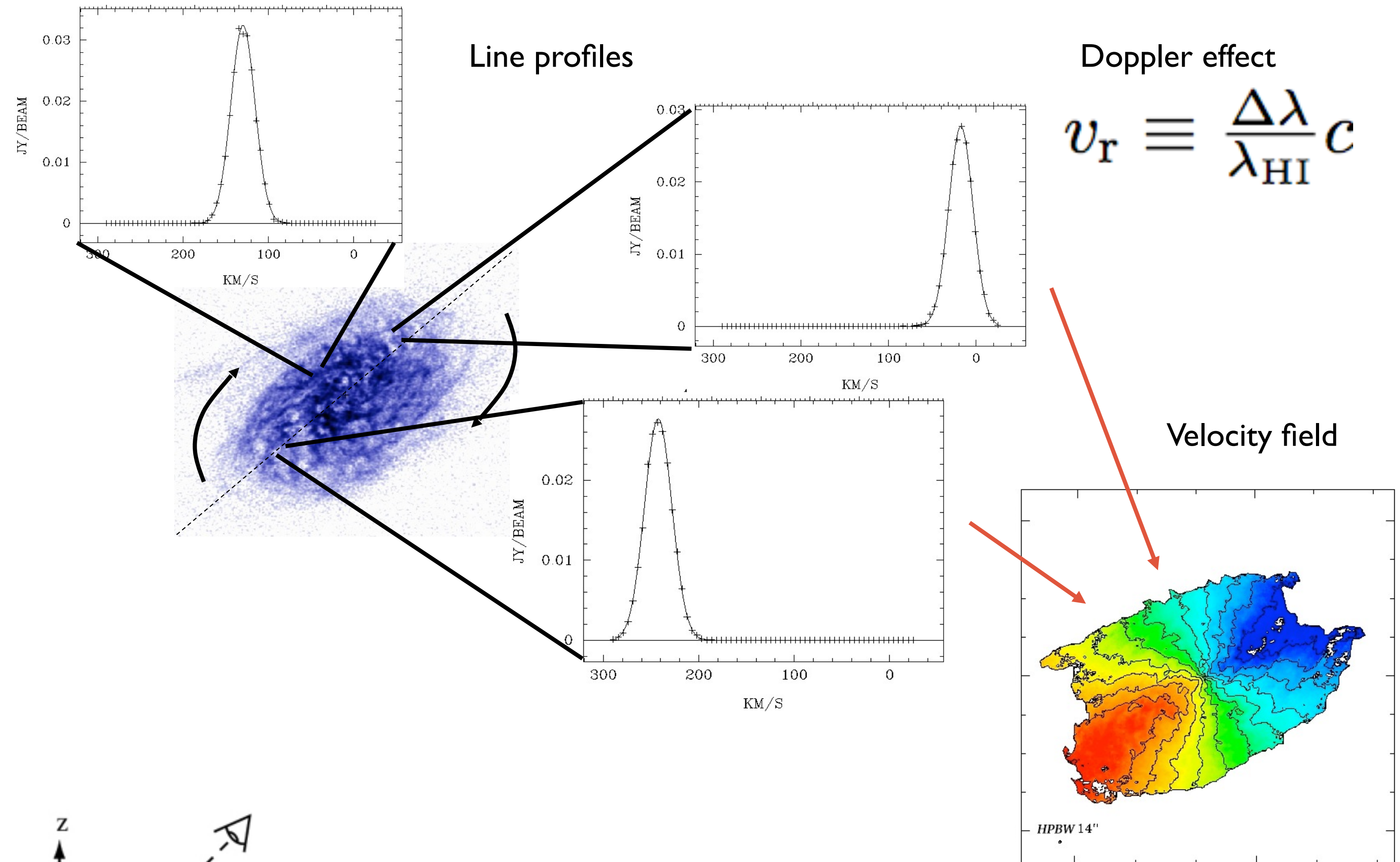
HI



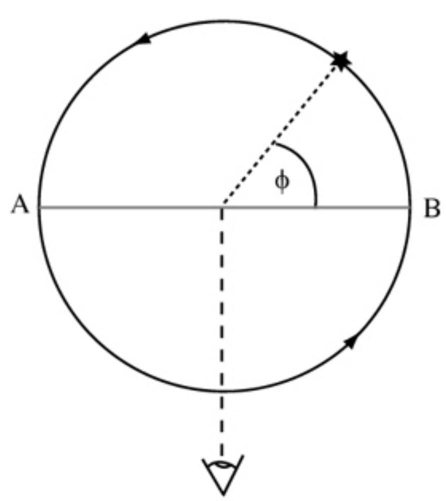
Contours of constant V(R)cosϕ

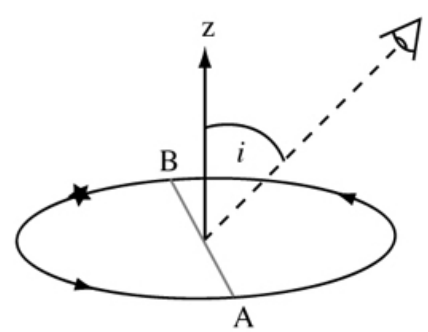


Rotational curves of disc galaxies



$$v_r \equiv \frac{\Delta\lambda}{\lambda_{\rm HI}} c$$





Viewed edge-on, the radial velocity measured is V_{sys} the systemic velocity of the galaxy.

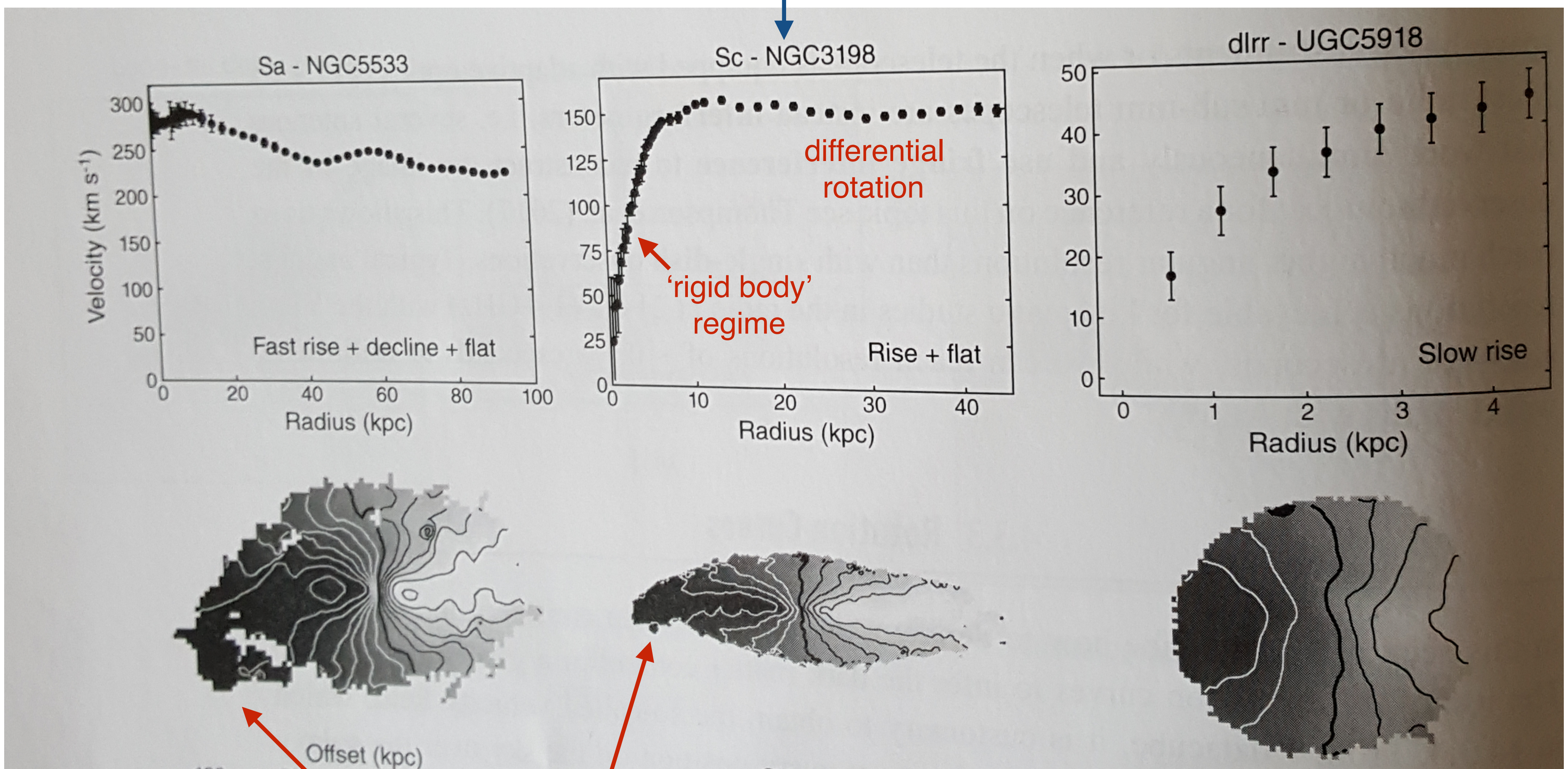
$$V_r(R, i = 90^\circ) = V_{\rm sys} + V(R)\cos\phi$$

When viewed at an inclination i, the radial velocity is projected to

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

Three main classes of rotation curves (spirals)

most typical



dwarf irregulars

approaching sides
(darker parts)

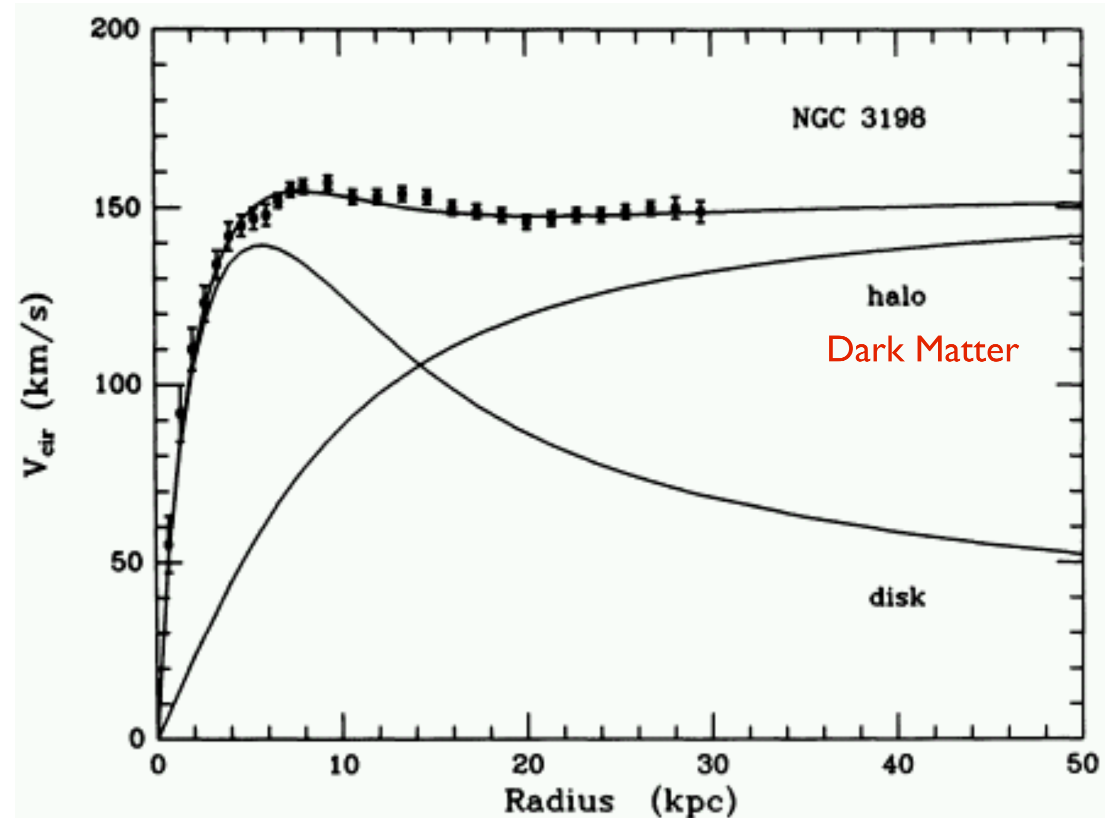
From Cimatti et al. book, section 4.3

HI rotation curves and disc galaxies

We can compare the HI rotation curve V(R) to that predicted from the luminous (stellar and gaseous) matter, using the observed surface brightness and density of the stars and gas

The rotation curve V(R) depends on mass, not luminosity, so we need to transform the surface brightness profile into a mass profile using M/L

But what is M/L for the disk? around the Sun we found, M/L~1–3 $M_\odot$



The contributions of the disk and bulge can be added since the potentials add linearly:

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

For all disc galaxies the luminous matter is never enough to make up all the mass inferred from the rotation curve: <u>dark matter halo</u>

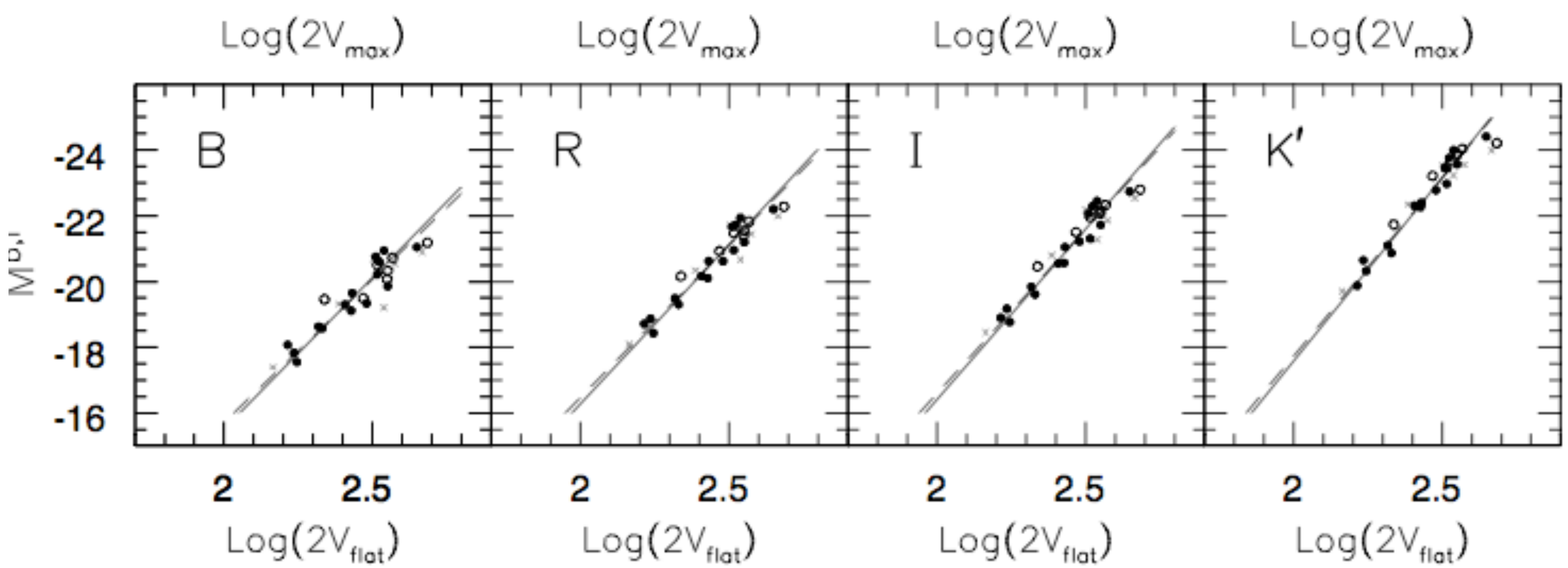
Note: the mass inferred from the HI rotation is a lower limit, as there maybe a lot of dark matter outside the region where there is gas and stars.

Existence of flat (or even rising) rotation curves at these radii imply additional unseen mass - **dark matter**.

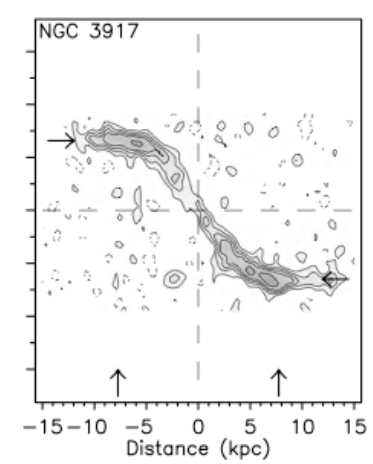
The Tully-Fisher relation

A relationship exists between the luminosity of a spiral galaxy and its maximum rotation velocity.

$$L \propto V_{\max}^4$$



amplitude of flat part of HI rotation curve



More scatter in B due to stellar population effects

The exponent changes with bandpass

Link between the stellar mass (luminosity) of a disc and the mass of the Dark Matter halo.

Verheijen 2001

Tully & Fisher 1977

The Tully-Fisher relation (cont.)

More luminous galaxies rotate faster

How does this come about?

Circular velocity and mass are related through $v^2 = \frac{GM}{r} \longrightarrow M \propto rv^2$

The flux and luminosity are related $I = \frac{L}{4\pi r^2} \longrightarrow r \propto \left(\frac{L}{I}\right)^{1/2}$

Assuming that M/L is constant $M = L \times \left(\frac{M}{L}\right) \propto rv^2 \propto \left(\frac{L}{I}\right)^{1/2} v^2$

$$L^{1/2}\left(\frac{M}{L}\right) \propto I^{-1/2} v^2 \longrightarrow L \propto v^4 \left(\frac{M}{L}\right)^{-2} I^{-1}$$

Assuming that M/L and I are constant $\boxed{L \propto v^4}$

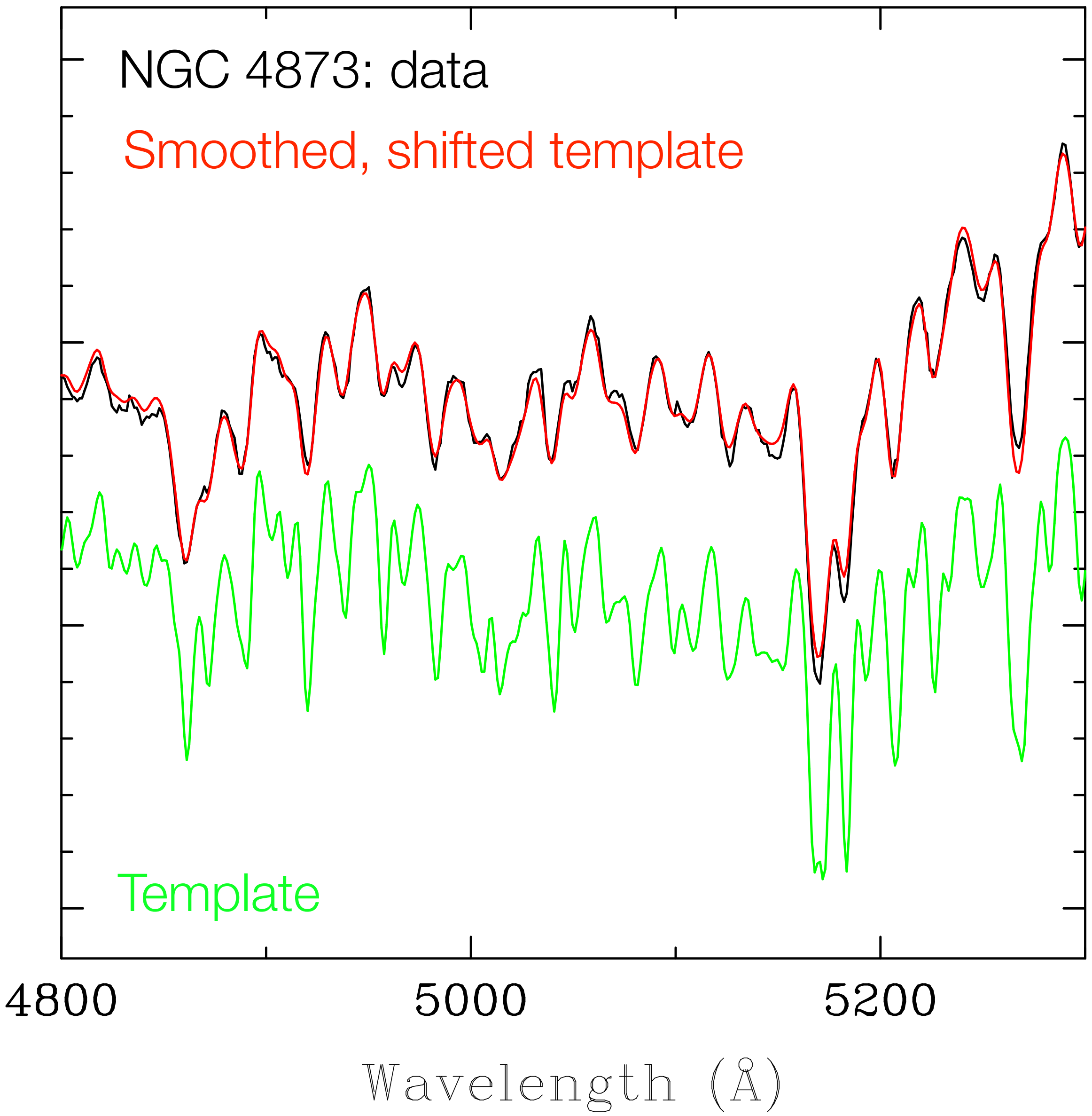
Stars & Dark Matter are linked…

Rot. veloc. in ellipticals from stellar absorption

How do we measure velocities in elliptical galaxies?

Use the absorption lines in the spectrum, which is the composite spectrum of all of the stars in the galaxy

Each star emits a spectrum which is then Doppler-shifted in wavelength according to its motion, which widens the absorption lines.



Rotation of ellipticals

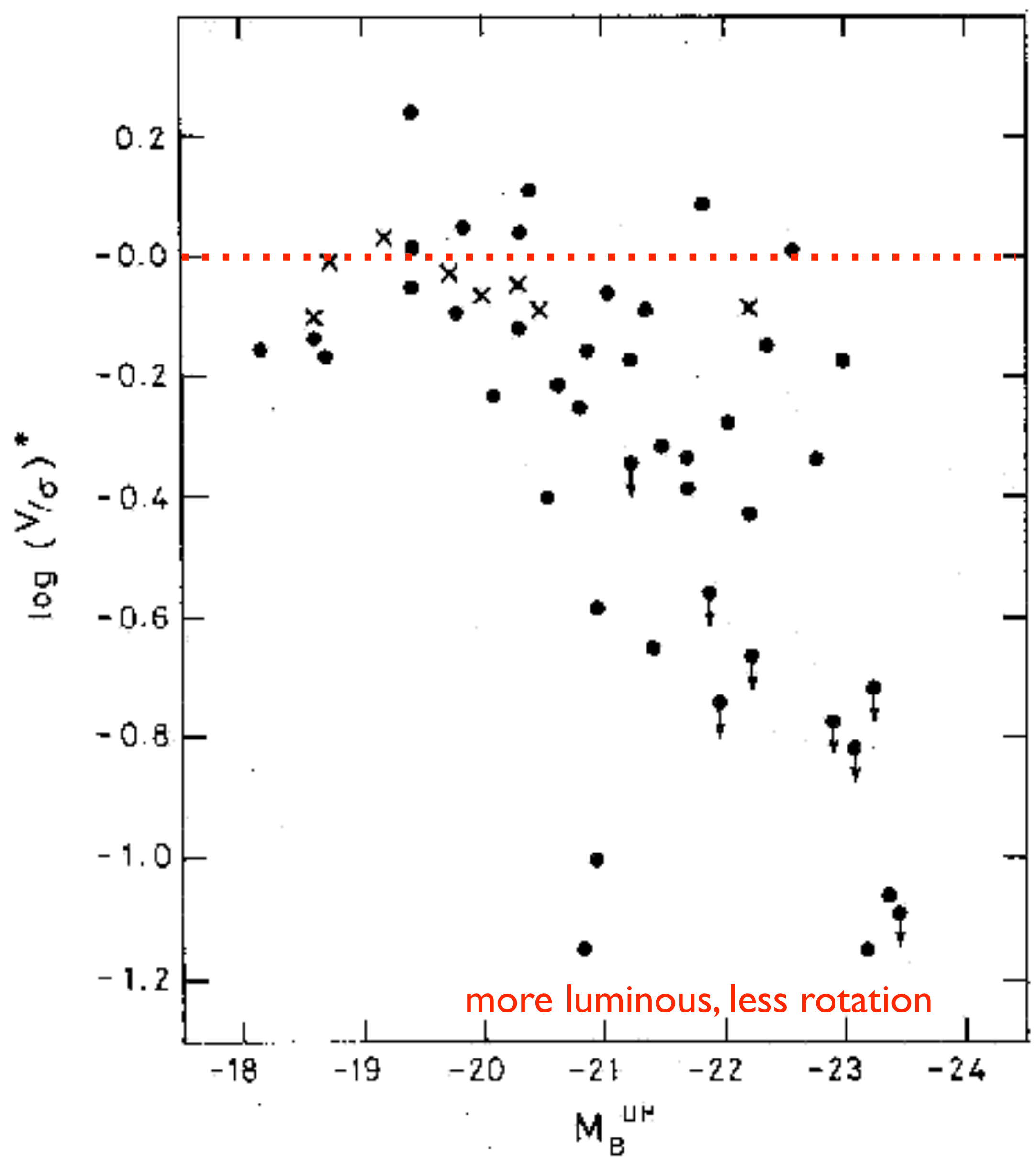


FIG. 4.—Log $(V/\sigma)^*$ against absolute magnitude. Ellipticals are shown as filled circles and the bulges as crosses; $(V/\sigma)^*$ is defined in § III*b*.

Rotational Properties of Elliptical Galaxies:

Anisotropy parameter:

$$\left(\frac{v}{\sigma}\right)^* \equiv \frac{v/\sigma}{\sqrt{\frac{1-b/a}{b/a}}} = \frac{(v/\sigma)_{\text{observed}}}{(v/\sigma)_{\text{rot. flattened}}}$$

see: Davies et al. (1983) *ApJ*, **266**, 41

$(\mathbf{v}/\sigma)^* \approx \mathbf{1}$ for rotationally flattened system

Rotation of ellipticals (cont.)

Ratio of rotation to dispersion plotted against projected ellipticity, for various galaxies.
Note that many Ellipticals have very little rotation, even though they are quite flattened.

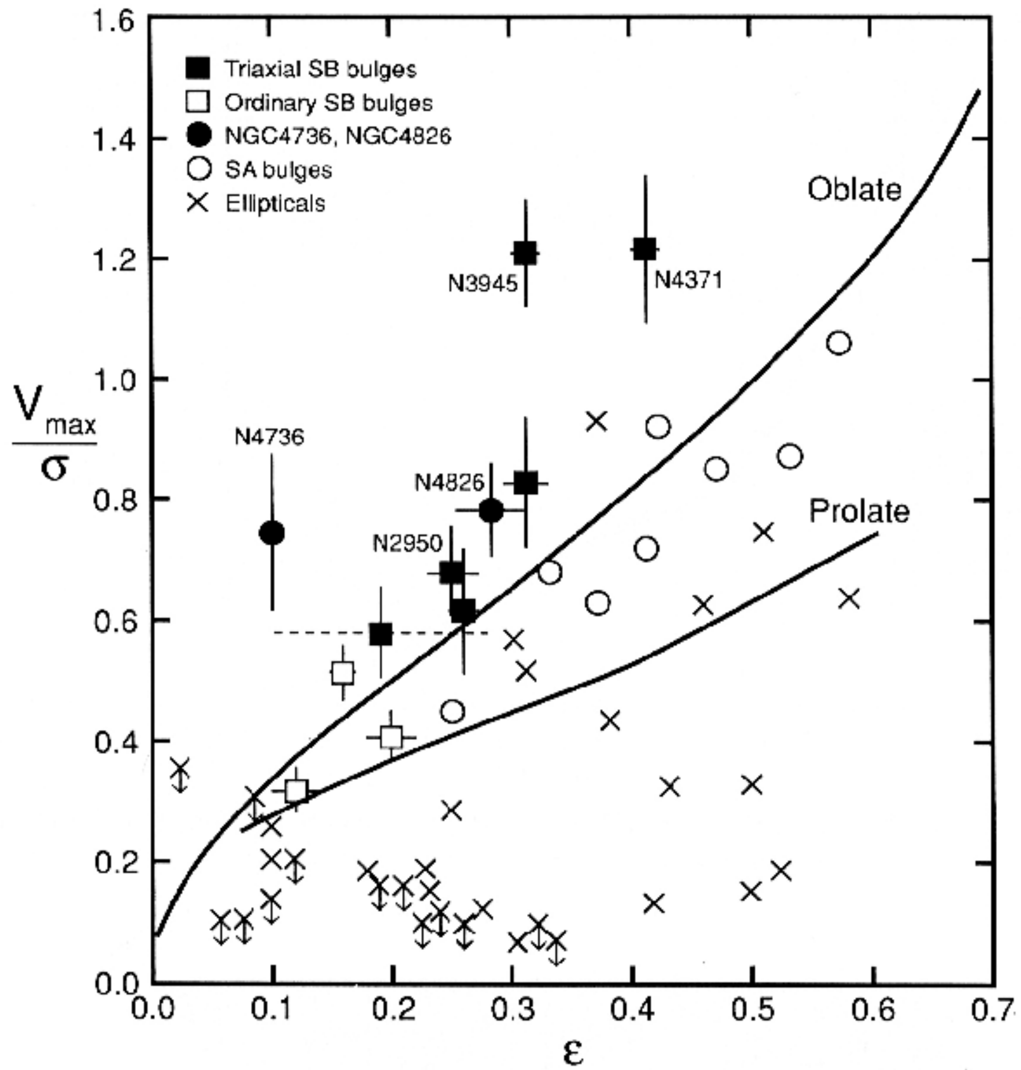


Fig. 3. $V_{max}/\sigma - \epsilon$ diagram for various kinds of stellar systems (cf. Kormendy 1982a).

Solid lines: amount of rotation necessary to account for observed ellipticity of galaxy relative to σ of stars.

Low luminosity Ellipticals and bulges rotate rapidly and have nearly isotropic velocity dispersions and are flattened by rotation

Bright Ellipticals rotate slowly and are pressure supported and owe their shapes to velocity anisotropy.

Most Ellipticals rotate too slowly for centrifugal forces to be the causes of their observed flattening.

This could be explained by proto-ellipticals acquiring angular momentum through tidal torques and then if mergers produce brighter ellipticals the rotation gets scrambled in the process.

Scaling relations of ellipticals

Because the relaxation times of elliptical galaxies are much longer than a Hubble time, these galaxies "remember" their formation.

Scaling relations tell us something about the formation process(es)

We'll start with scaling relations between structural parameters, like luminosity, velocity dispersion, and surface brightness...

One of the earliest known structural scaling relations was the Faber-Jackson relation:

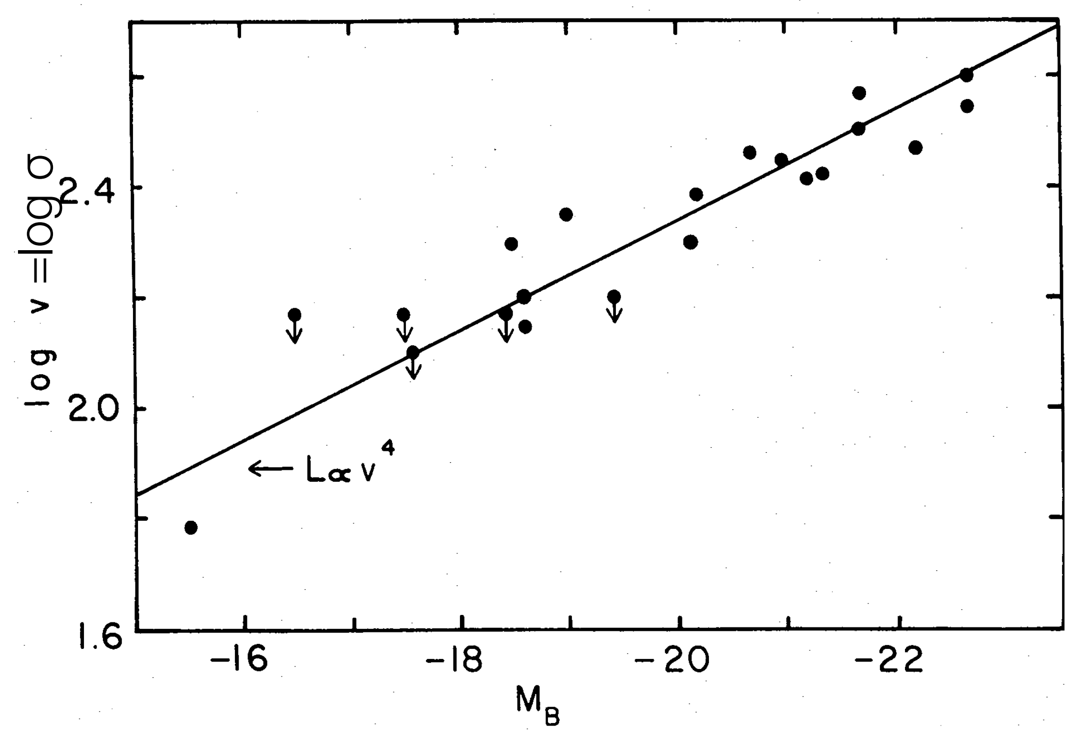
$$L \propto \sigma^4$$

strong correlation between luminosity (L) and central velocity dispersion (σ)

A natural consequence of the virial theorem.

Plenty of scatter, and the slope of the relation is different than the virial theorem.

This was assumed to indicate a missing parameter… and there was originally a lot of debate about what was the missing parameter..



Faber & Jackson 1976 ApJ, 204, 668

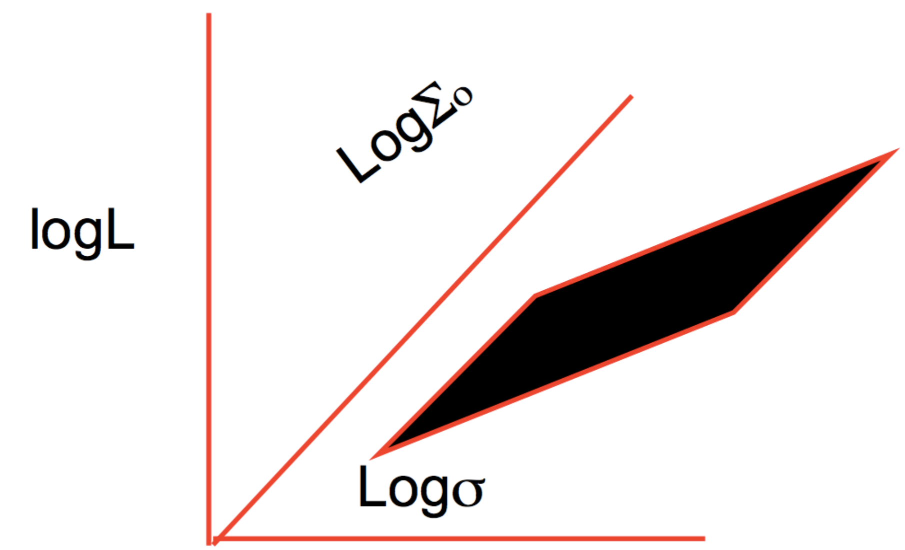
The fundamental plane for ellipticals

A break through in understanding of scaling laws came from large homogeneous data sets (from CCDs & long-slit spectroscopy), and the application of statistical tools.

__plane__ - means correlation in a 3D space and we see this space with three parameters that "see" the correlation from different angles.

$$R \propto \sigma^{1.24} \langle I \rangle_e^{-0.82}$$

Size | Velocity Dispersion | Luminosity



The mass-to-light ratios of ellipticals increases as they become more luminous (or more massive)

Likely because larger galaxies are older

The fundamental plane for ellipticals (cont.)

<u>Virial Theorem</u>: for a stable, self-gravitating, spherical distribution, the total kinetic energy is equal to minus 1/2 times the total gravitational potential energy.

Where does the Fundamental Plane of elliptical galaxies come from?

Assume the Virial Theorem holds, then the mass is $$M = V^2 R/G$$

Divide this by the area to get the mass surface density: $$\eta = \frac{M}{\pi R^2} \propto \frac{V^2}{R}$$

The surface brightness is this divided by the mass-to-light ratio: $$I = \eta \left(\frac{M}{L}\right)^{-1}$$

combining this: $$I \propto \frac{V^2}{R(M/L)}$$

$$I_e = \frac{L}{2\pi R_e^2}$$

Rewrite this in terms of the radius R_e=R and identifying the velocity V as the velocity dispersion σ, we have $$R_e \propto \left(\frac{M}{L}\right)^{-1} \sigma^2 \langle I \rangle_e^{-1}$$

But note the <u>observed</u> coefficients aren't 2 & -1 (they range from 1 to1.4 and from -0.75 to -0.9) and so this implies

observed relation:

$$R \propto \sigma^{1.24} \langle I \rangle_e^{-0.82}$$

$$\boxed{\frac{M}{L} \propto L^{1/4}}$$

The more luminous Ellipticals have higher M/L