

# How did the Local Group form?

- Age of stars  $\sim$  0-12 Gyr
- Most dSph no longer forming stars and in orbits around MW or M31
- Most dlrr are forming stars and are “free fliers”
- Metallicity very low in oldest globular clusters
  
- Look at virial temperature
- Look at Jean’s mass
- Look at timescale for collapse
- Top-down or bottom-up?

**Homologous collapse** Virial Theorem  $U + 2K = 0$  equilibrium cond.

The condition that  $U > 2K$  leads to

$$\frac{3M_c kT}{\mu m_H} < \frac{3}{5} \frac{GM_c^2}{R_c}.$$

Assuming constant density,  $R$  is given by:

$$R_c = \left( \frac{3M_c}{4\pi\rho_0} \right)^{1/3}$$

So, if  $M_J > M_c$  we have collapse and the minimum mass that does this is the Jean's mass:

$$M_J \simeq \left( \frac{5kT}{G\mu m_H} \right)^{3/2} \left( \frac{3}{4\pi\rho_0} \right)^{1/2}$$

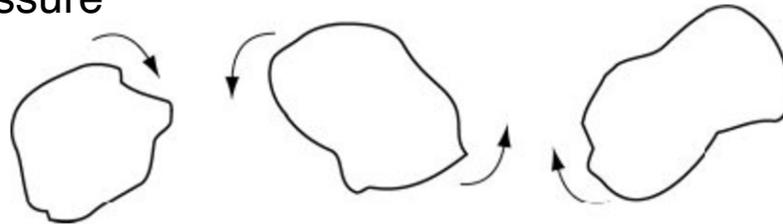
Which has a radius:

$$R_J \simeq \left( \frac{15kT}{4\pi G\mu m_H \rho_0} \right)^{1/2}$$

At  $z=1100$   
 $T \sim 3000$  K  
 $M_J \sim 10^7 M_{\text{Sun}}$   
 $R_J \sim 1$  kpc

# Protogalaxies form near Large Mass Concentrations

After recombination at  $z=1100$  universe becomes transparent, gas no longer supported by radiation pressure

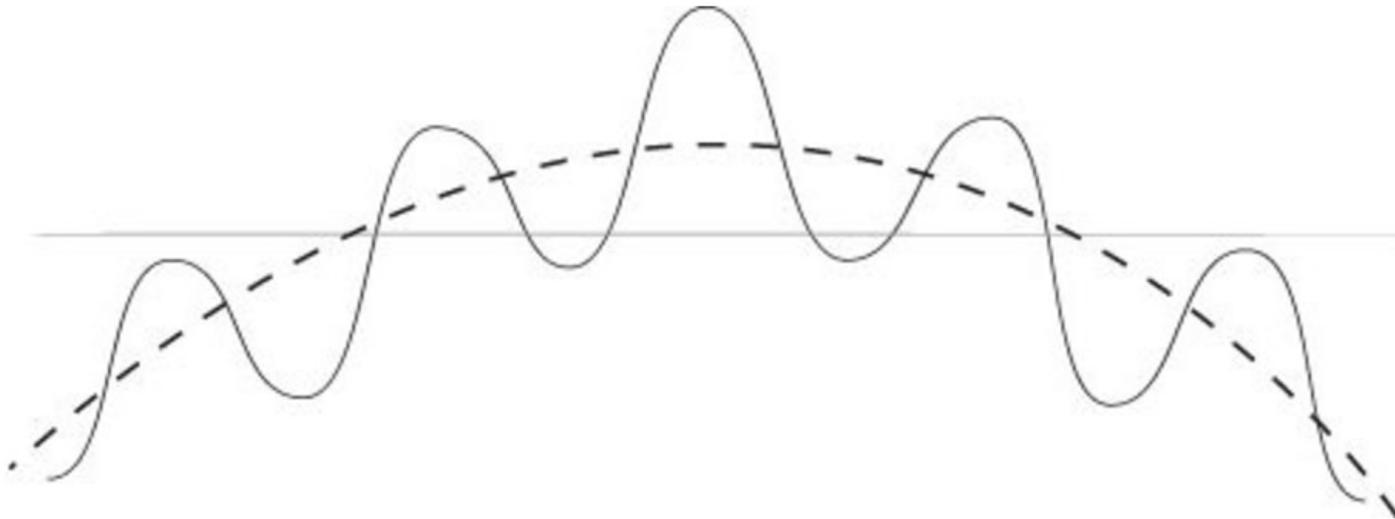


Stars form early inside  $\sim 10$  million  $M_{\text{sun}}$  clumps

Dense regions can collapse, develop rotation from gravitational torques

Aggregate into galaxies or end up in orbit around them

Collisions of clumps can drive star formation



## Eggen, Lynden-Bell & Sandage (ELS)

- Because of orbit eccentricity, and  $E_z$ ,  $L_z$  are adiabatic invariants (if potential changes slowly, they should be conserved)
  - Metal-poor stars must have formed on eccentric orbits
  - or violent star formation history
- Basic paradigm: MW formed from a  $\sim$ spherical cloud of rotating, metal-poor gas.
  - Exceeds Jeans mass, free-fall collapse
  - Most metal-poor stars and halo glob. cluster stars form here
  - SN from this pop increased metallicity
  - Remaining gas collapses into metal-rich disk, subsequently forming younger disk stars and clusters.

Milky Way formed from rapid collapse of a proto-galactic nebula in  $<10^9$  yrs. This is a *top-down* process.

## Problems

- Need high initial SFR 100-1000  $M_{\odot}/\text{yr}$
- Doesn't explain
  - thin/thick disk components
  - stars of different ages in the bulge
  - Continued growth of the MW
  - retrograde motion of some halo stars
  - dynamical clumps of stars in halo (moving groups)
  - age differences and metallicity differences in globular clusters (age spread  $\sim 3\text{Gyrs}$ )
- No treatment of dark matter (well, it was 1962...)

## **A more modern view**

Larson 1969, Searle & Zinn 1978 etc (SZ)

- Suggest MW formed from collapse of individual gas clouds
  - metallicity of those components depend on number of SN explosions occurring before gas blown away by kinetic energy of SNe.
  - Accounts for the fact that metallicities of halo GC spread over large range (not formed of same material)
- Unclear how disk is formed

## Basic SZ

- At time of galaxy formation, expect Jeans mass of  $10^6$ - $10^8 M_{\odot}$
- 100s-1000s of dark-matter dominated fragments collided and merged to create each giant galaxy.
  - Leftovers + smaller events created dwarfs.
  - recently plenty of observations of nearby dwarfs
- *Bottom-up* process - small pieces merged together as stars form.
- Early on, gas in some fragments collapse to form globular clusters.
  - Perhaps 1000s in the MW initially, now only  $\sim 150$  left (the dense cores that could survive tidal disruption)

- Collisions between fragments heat proto-galaxy, slowing the collapse
  - age spread of halo and thick disk
- Collapse is fastest where the density is highest
  - recall  $t_{\text{ff}} \propto \rho^{-1/2}$
  - $\rho$  highest in *inner* region => central bulge
  - This is where chemical enrichment would be fastest
    - we do observe old, metal-rich stars in the central bulge

- Also, massive fragments subject to dynamical friction, fed bulge.
  - Why massive? Recall

$$f_d = \frac{CG^2 M^2 \rho}{V_m^2}$$

- Remaining gas eventually settled into rotating disk
- Further accretion events => bulge and thick disk growth, age spread.
- OR: thick disk formed when collapsing structure had  $10^6$  K, with scale height  $\sim 1$ -2 kpc, thin disk formed later as gas cooled

## **SZ pro's and con's:**

- Explains
  - retrograde halo stars and moving groups
  - different metallicities and ages of halo GCs
  - Continued growth of MW
- Does not include dark matter
- Does not explain formation of disk
- Real evolution could be somewhat more complex

# Astronomy 537

Lecture 9: Spiral Galaxies I



## **Announcements**

- HW #2 Due today
- Teaching Topics posted
- Syllabus slightly revised, Exam#1 now on March 4

## **Spiral Galaxies**

The most common of the giant galaxies

Produce most of the light in the local Universe

Density in the bulge can be 10,000 times greater than in the disk

The presence of a spiral indicates gas is still present

# Journal Class

- **The Case for the Fundamental  $M_{\text{BH}}-\sigma$  Relation**

- Marsden et al. 2020

Discussion leader: **Mark Burch**

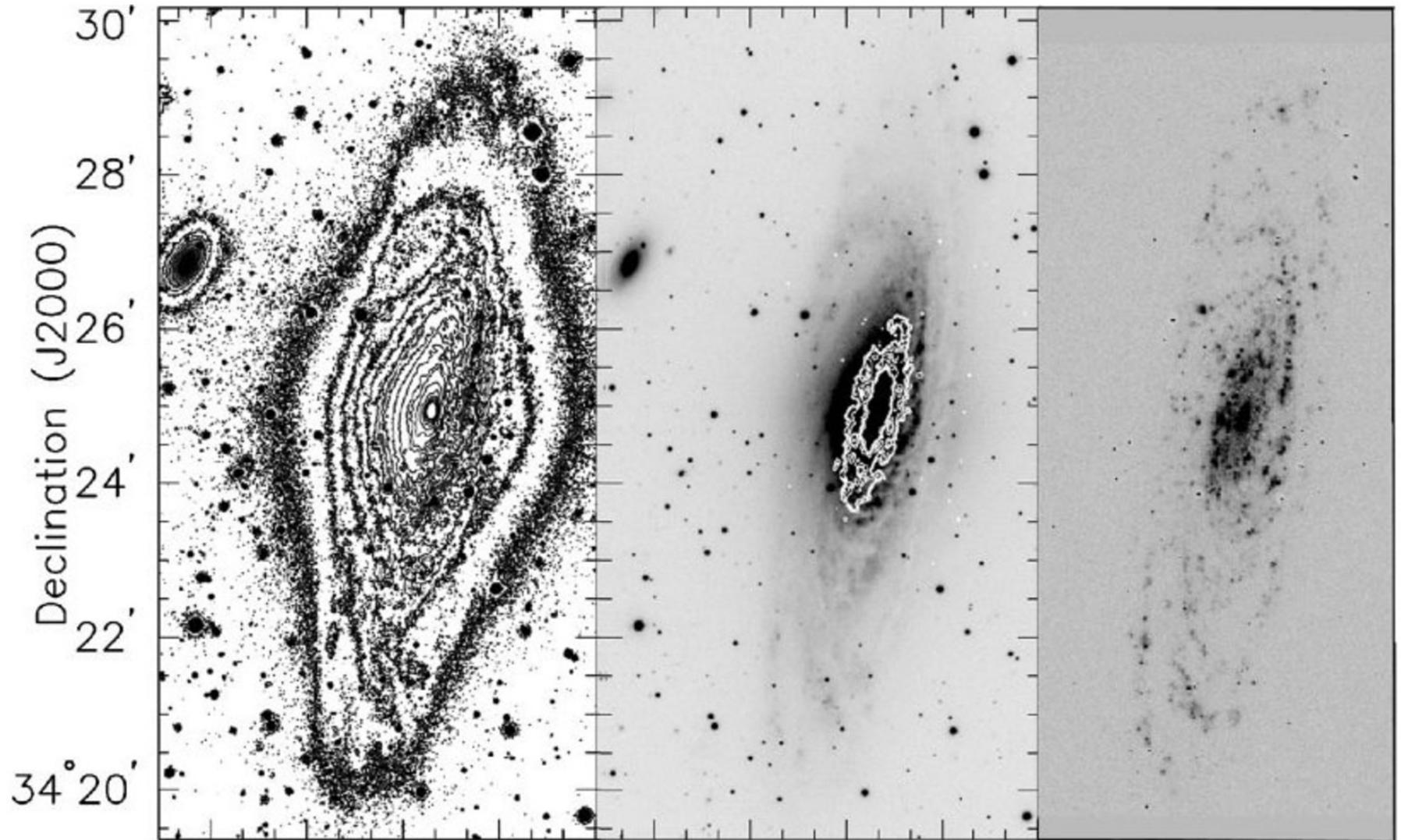
Note: To encourage discussion everybody must pose at least one question during the group discussion

# NGC 7331

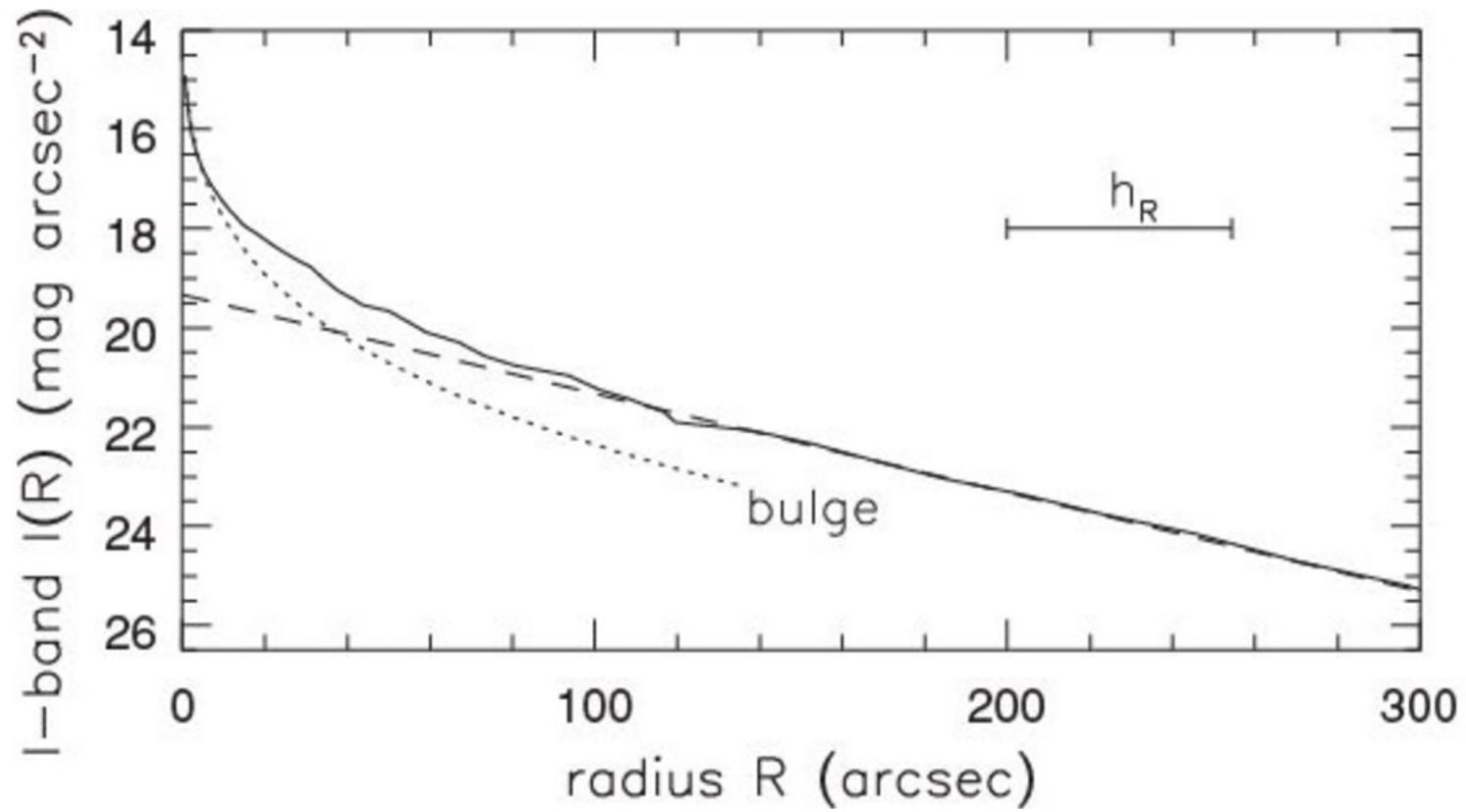
Optical

optical + CO

Halpha



# NGC 7331

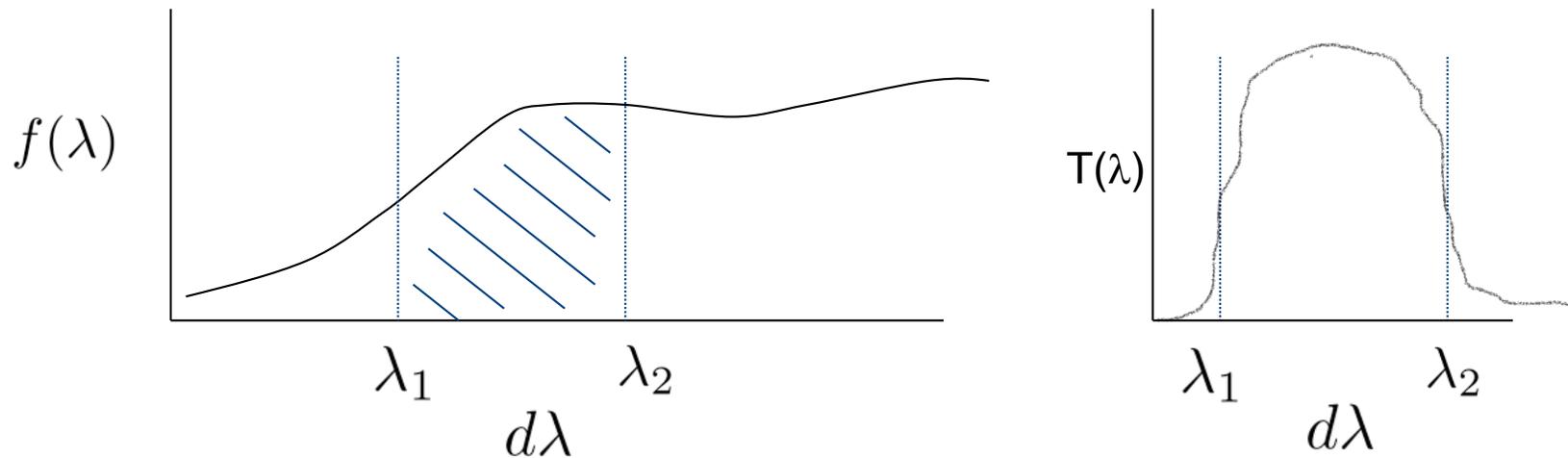


# How to compare galaxies properly



## K-corrections

Normally we observe through filters = over some specific  $d\lambda$ . For a typical galaxy spectrum at  $z=0$ :

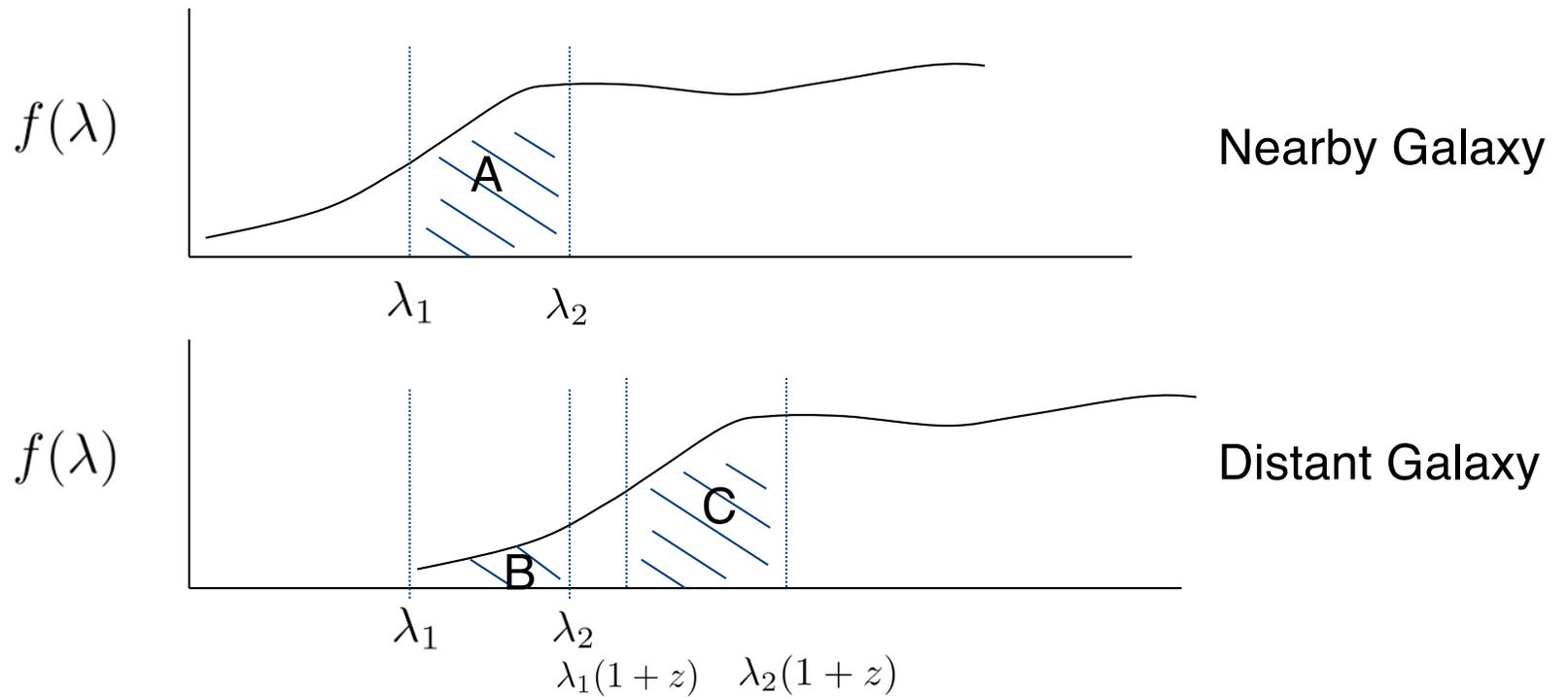


$$L = \int_{\lambda_1}^{\lambda_2} f(\lambda) d\lambda = \int_0^{\infty} T(\lambda) f(\lambda) d\lambda$$

where  $T$  is the filter transfer function.

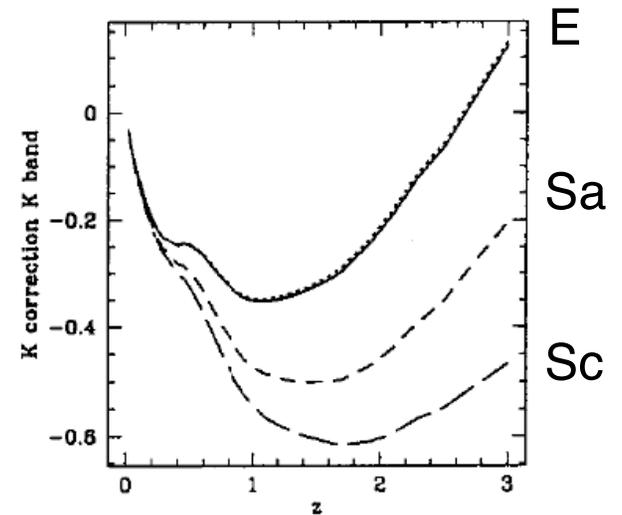
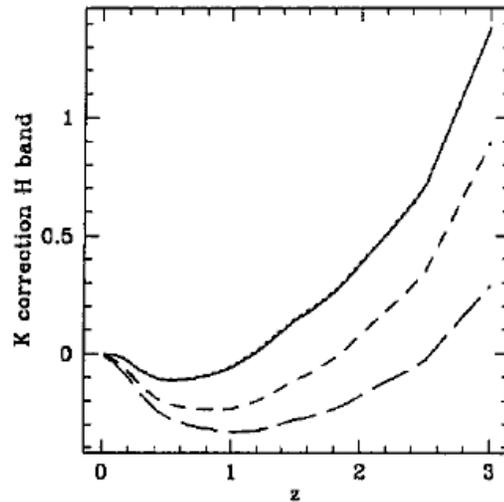
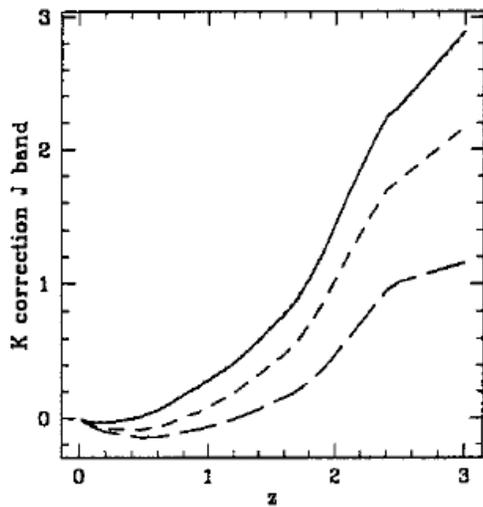
- Due to redshift effects, the light emitted between  $\lambda_1$  and  $\lambda_2$  becomes light observed between  $\lambda_1(1+z)$  and  $\lambda_2(1+z)$ . Thus both wavelength and bandpass change!
- Looking at galaxies at higher  $z$  through same filter, we therefore receive emission from shorter wavelengths at a slower rate.
- Knowing the spectral shape, we can correct for this via the *K-correction*.

*(origin of the term K-correction has been attributed to both Hubble and Wirtz)*



We measure B, but want to measure C to compare to A.

$$K(z) = \frac{\int_0^\infty T(\lambda/(1+z))f(\lambda/(1+z))d\lambda}{(1+z) \int_0^\infty T(\lambda)f(\lambda)d\lambda}$$



Poggianti 1997

K correction in J, H and K band for three types of galaxies.

Typically given as

$$K(z) = az + bz^2$$

Type	a	b
E/S0	3.13	0.24
Sabc	2.63	-0.107
Sd/Irr	0.62	0.14

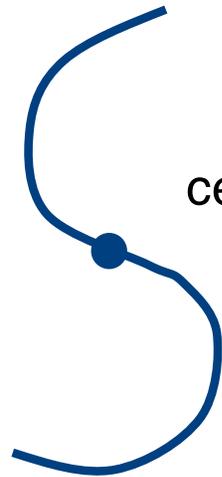
(V-band values)

- K-corrections in the optical band large for elliptical galaxies, since they emit little flux in the UV.
- Smaller corrections for spirals and irregulars.
- K-corrections depend on observed filter:
  - smaller as you observe further in the red
  - negative in the near-IR

## Surface brightness

To quantify the stellar content, look at the total luminosity (in some filter) of a galaxy. How? They don't have sharp edges.

Define *surface brightness* as  $\mu = \text{flux}/\text{angular area}$  (mag/arcsec<sup>2</sup>).

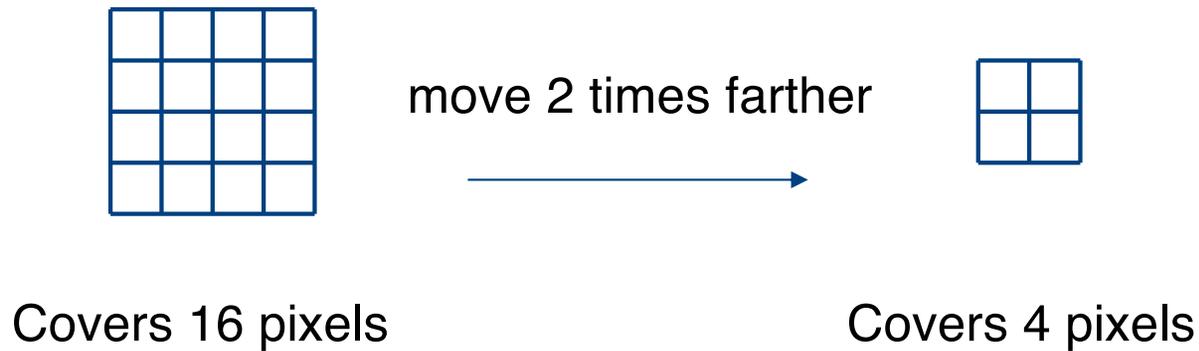


centrally, in B filter,  $\mu_B \sim 21$  mag/arcsec<sup>2</sup>

further out,  $\mu_B \sim 25$  mag/arcsec<sup>2</sup>

Surface brightness is independent of distance.

Why? Consider a square galaxy.



Total flux is 4 times less, but number of pixels (angular area) less by the same factor.

## Isophotes

Contours of constant surface brightness are *isophotes*.

Measures of galaxy 'size'

1. Holmberg radius

$r_H$  = semi-major axis of the

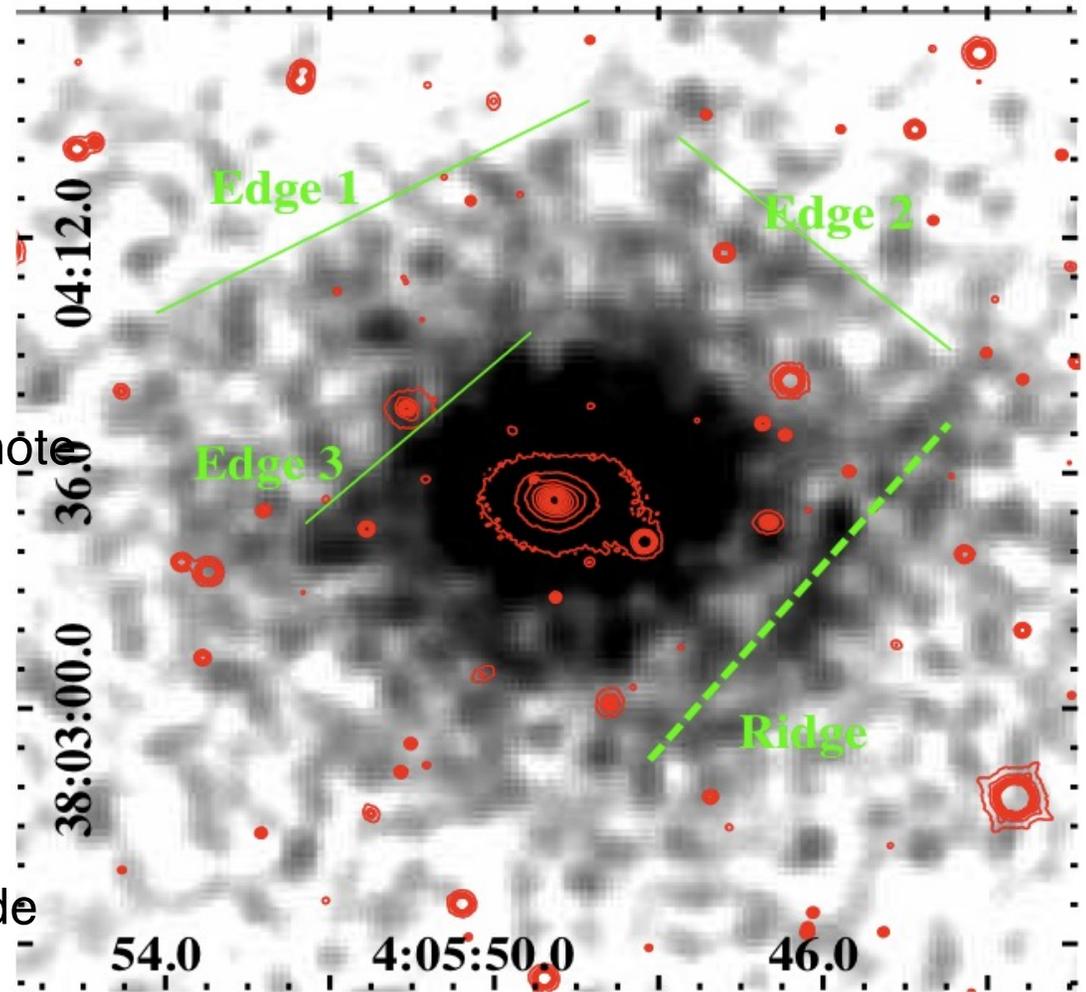
$\mu_B \sim 26.5$  mag/arcsec<sup>2</sup> isophote

2.  $r_{25}$  = same idea but for

$\mu_B \sim 25$  mag/arcsec<sup>2</sup>.

Luminosity or absolute magnitude

refers to light within  $r_H$  or  $r_{25}$ .



Chandra X-ray (greyscale) compared to K band

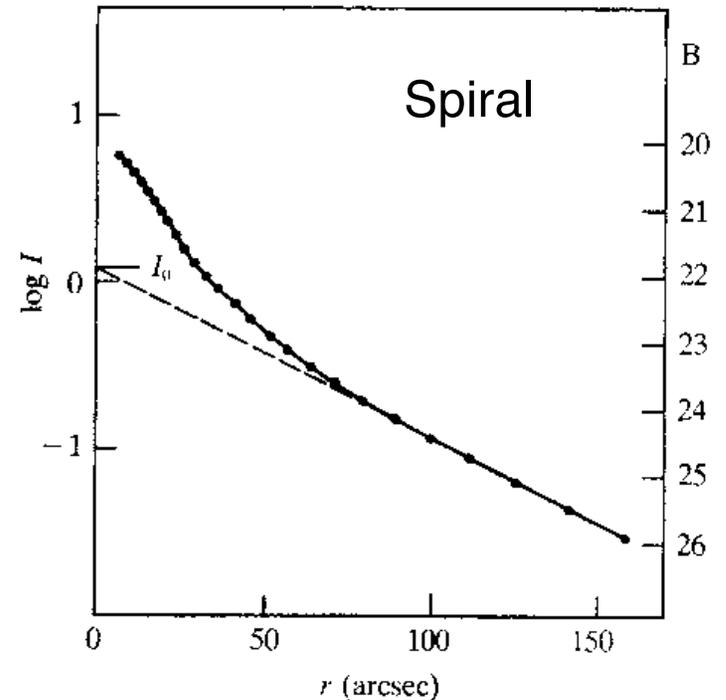
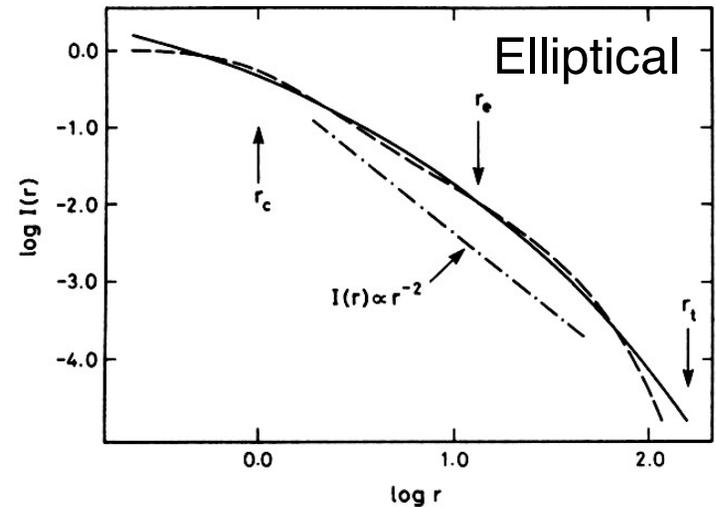
## Light distribution

Ellipticals have de Vaucouleur profiles,  $r^{1/4}$  (solid line in figure).

Disks have exponential profiles,  $e^{-r/r_0}$ .

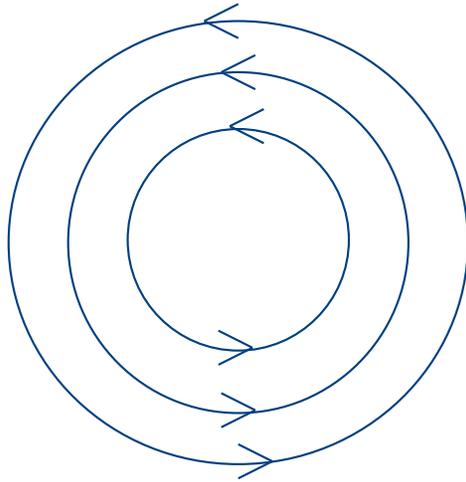
Spirals have the combination of the above due to the bulge and disk components.

Isophotes measure the distribution of luminous matter in galaxies. To estimate distribution of dark matter we need rotation curves.



## Rotation curves and mass measurements of spirals

Rotation causes Doppler shift of spectral lines



Most common: HI 21cm, CO,  $H\alpha$  = ISM emission lines.  
Stellar absorption lines are much, much fainter.



## Mass determination

Recall for a given mass distribution

$$\frac{mv^2(r)}{r} = \frac{GM_r m}{r^2}$$

$m$  = mass of e.g. star

$M_r$  = galactic mass within  $r$

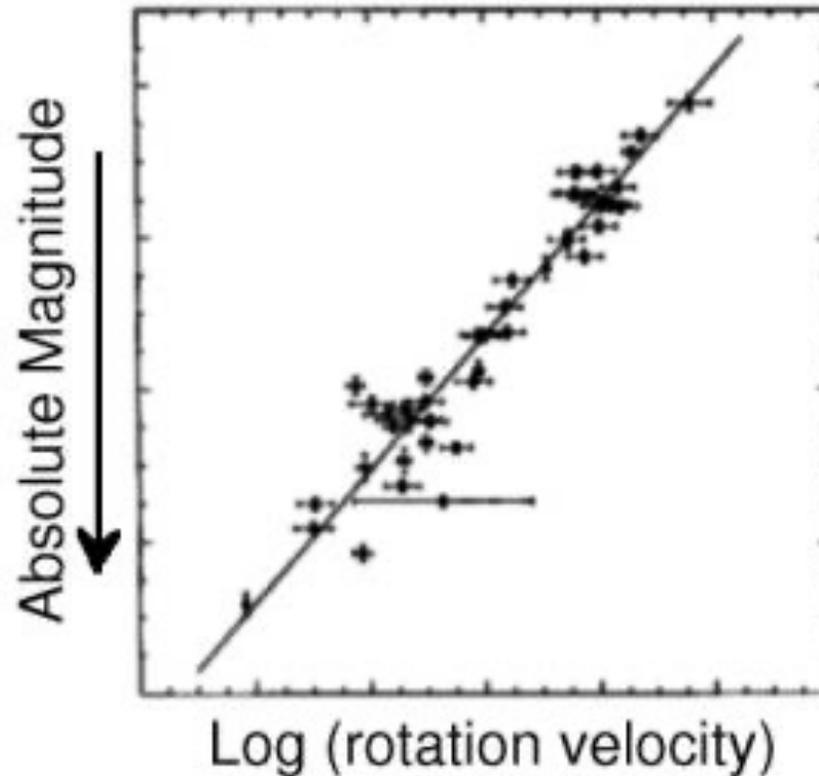
$V(r)$  = rotation speed

$$M_r = \frac{rV^2(r)}{G} = \int_0^r \rho(r)4\pi r^2 dr$$

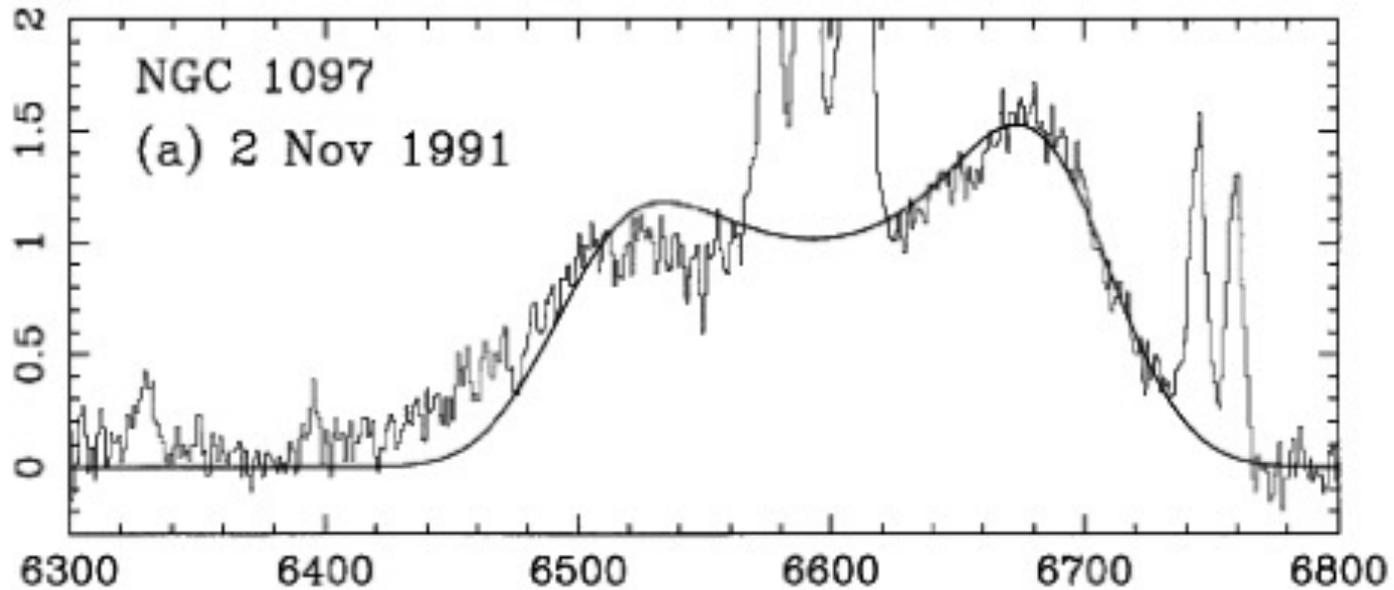
So if  $V(r)$  constant, then  $M_r \sim r$  (haven't reached 'edge').

## Correlations

Rotation curves can be correlated with luminosity. This is the *Tully-Fisher relation*. The higher the luminosity, the higher the maximum rotational velocity.



Exact form depends of type: Sa, Sb, Sc

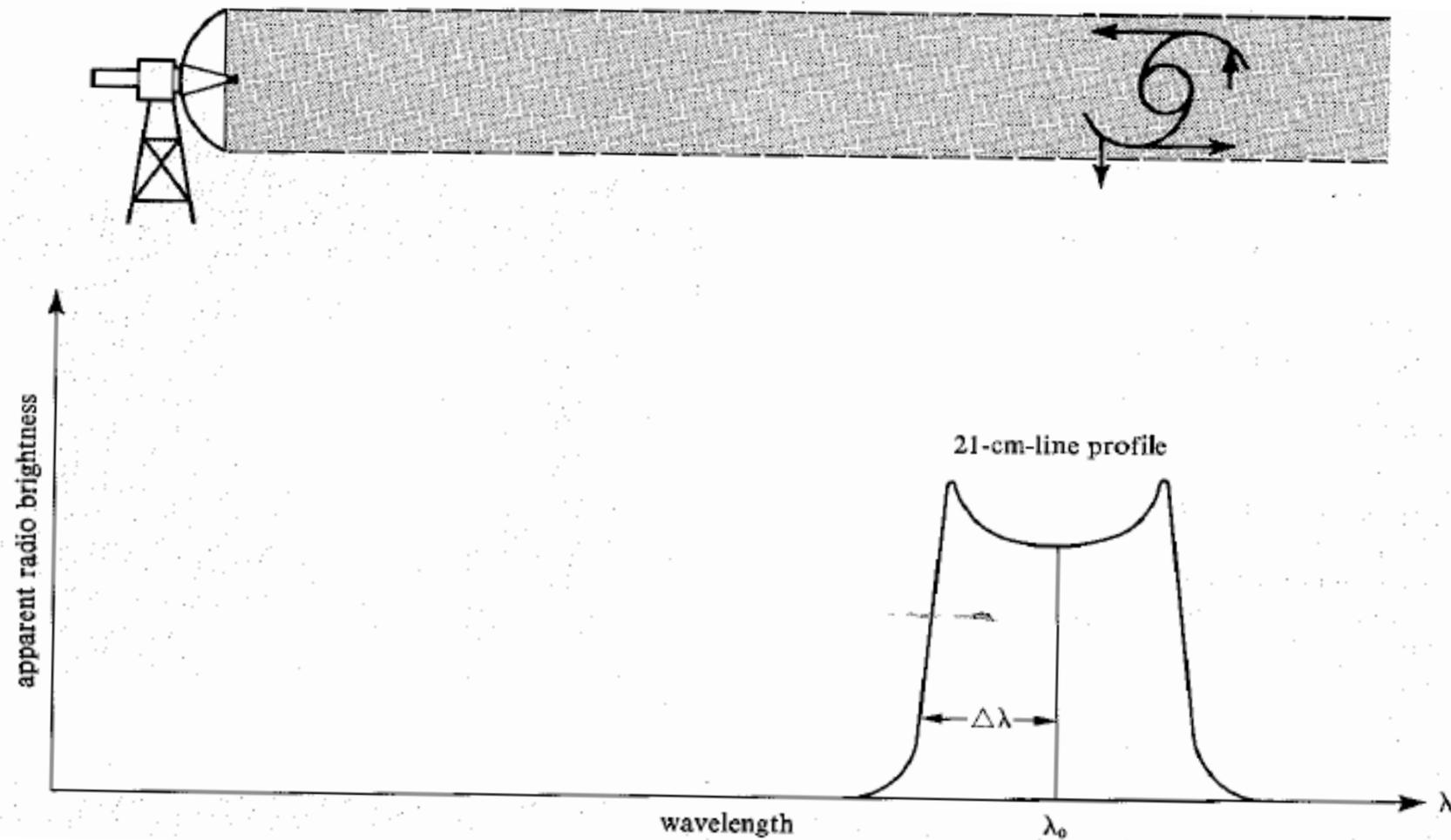


Spirals display double-peak profiles (lots of matter rotates at same velocity for flat rotation curve).

$$\frac{\Delta\lambda}{\lambda} \simeq \frac{V_r}{c} = \frac{V \sin i}{c}$$

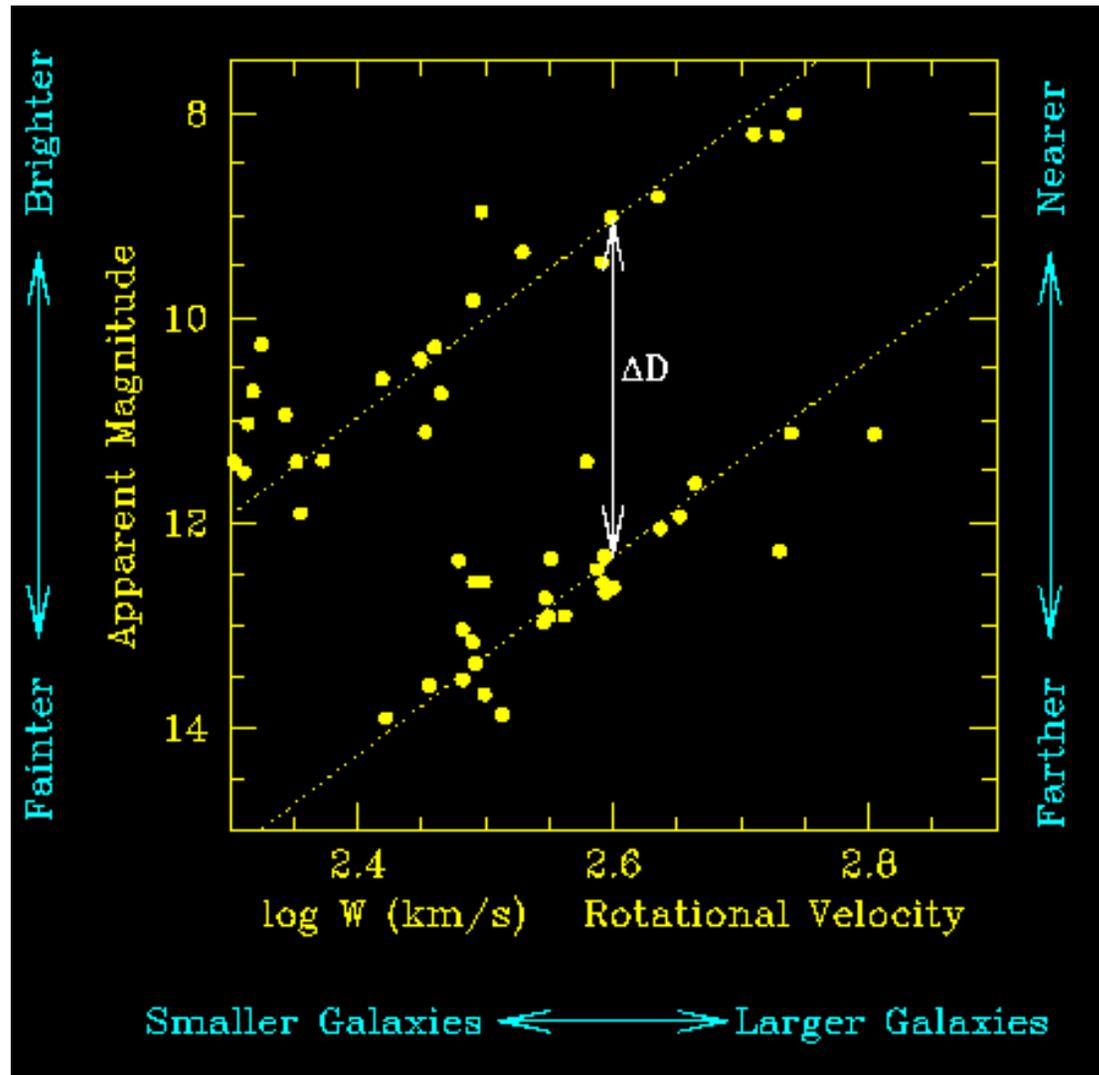
Tully-Fischer:  $L \propto V_{max}^{\alpha} \quad \alpha \sim 4$

Hence, basically a plot between luminosity and mass of a galaxy - not surprisingly correlated. With the luminosity determined, you can calculate the distance.



$$\frac{\Delta\lambda}{\lambda} \approx \frac{V_r}{c} = \frac{V \sin i}{c}$$

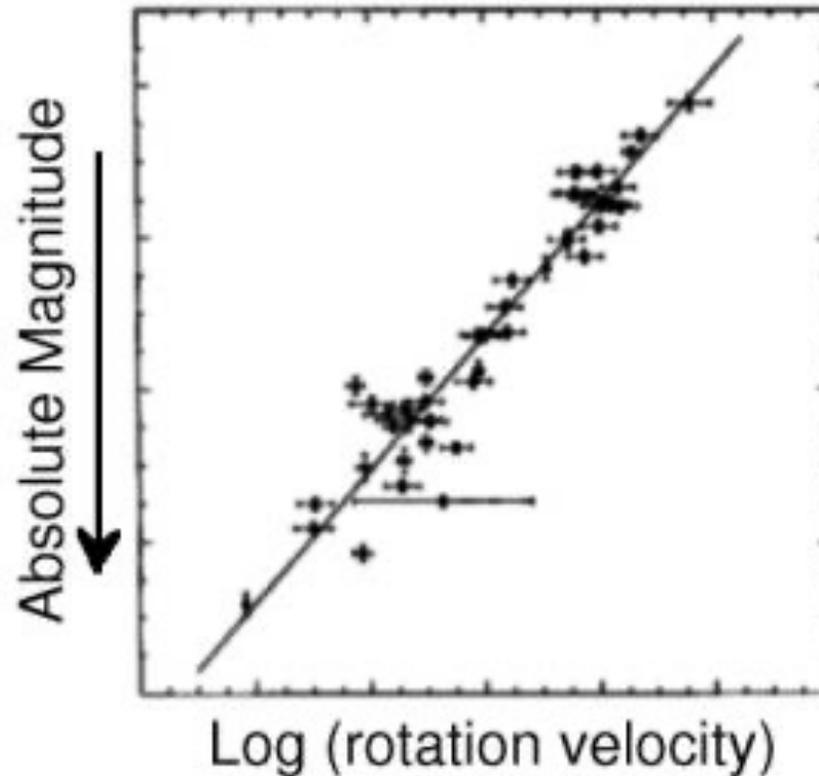
Tully-Fisher relations of two clusters at different distances.



Also note, the more massive a galaxy is, the faster it rotates.

**Worksheet:** Derive the relationship between  $L$ , luminosity, and  $v$ , velocity for the Tully-Fisher relationship. You can assume a constant  $M/L$  ratio for all galaxies, and that the surface brightness, given by  $L/R^2$  is also constant.

$$L \propto V_{max}^\alpha \quad \alpha \sim 4$$



## Where does Tully-Fisher derive from?

Start with gravitational force = centripetal force

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \Rightarrow M = \frac{v^2 R}{G}$$

Assume roughly constant mass-to-light ratio for spirals

$$C_{ML} = \frac{L}{M}$$

Roughly constant surface brightness for spirals

$$C_{SB} = \frac{L}{R^2}$$

$$L = \frac{C_{ML}^2 v^4}{C_{sB} G^2}$$

Recall 
$$M = M_{\odot} - 2.5 \log \left( \frac{L}{L_{\odot}} \right) =$$
$$= M_{\odot} - 2.5 \log V_{max}^4 - 2.5 \log C + 2.5 \log L_{\odot}$$

$$M = -10 \log V_{max} + C$$

But, M/L is not same for all spirals:

Sa  $\left\langle \frac{M}{L_B} \right\rangle = 6.2 \pm 0.6$

Sb  $\left\langle \frac{M}{L_B} \right\rangle = 4.5 \pm 0.4$

Sc  $\left\langle \frac{M}{L_B} \right\rangle = 2.6 \pm 0.2$

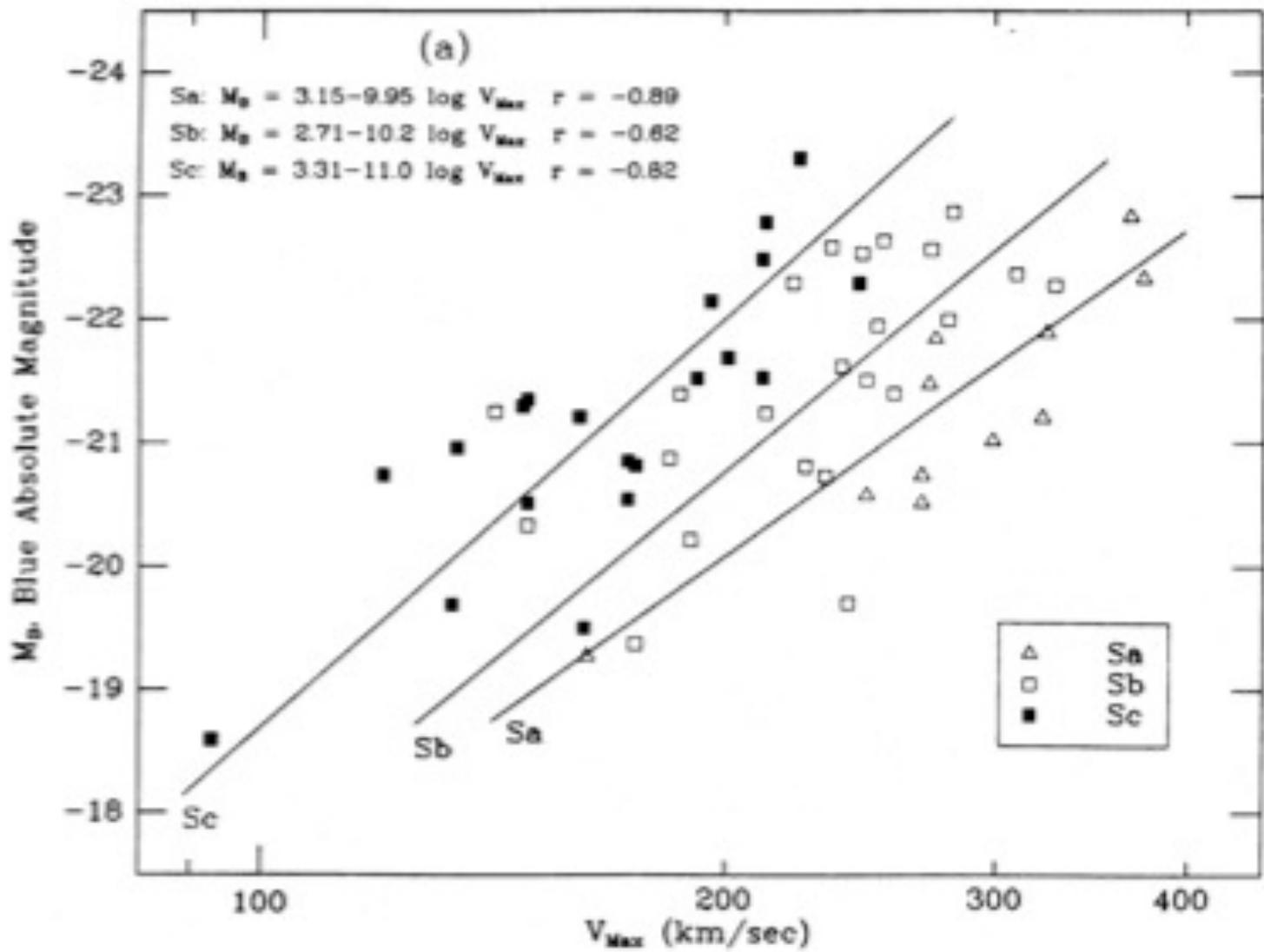
So the Tully-Fisher relations are slightly different:

Sa  $M_B = -9.95 \log V_{max} + 3.15$

Sb  $M_B = -10.2 \log V_{max} + 2.71$

Sc  $M_B = -11.0 \log V_{max} + 3.31$

Rubin et al 1985



## Integrated colors of galaxies

red



blue

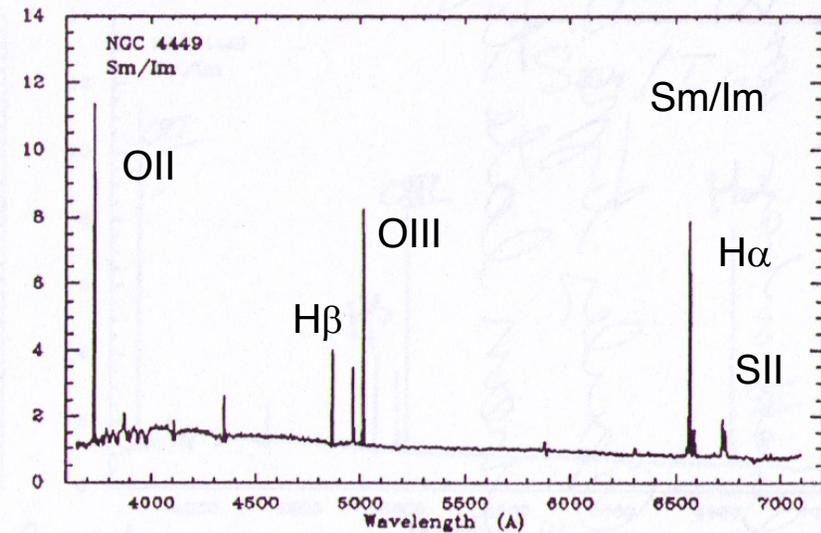
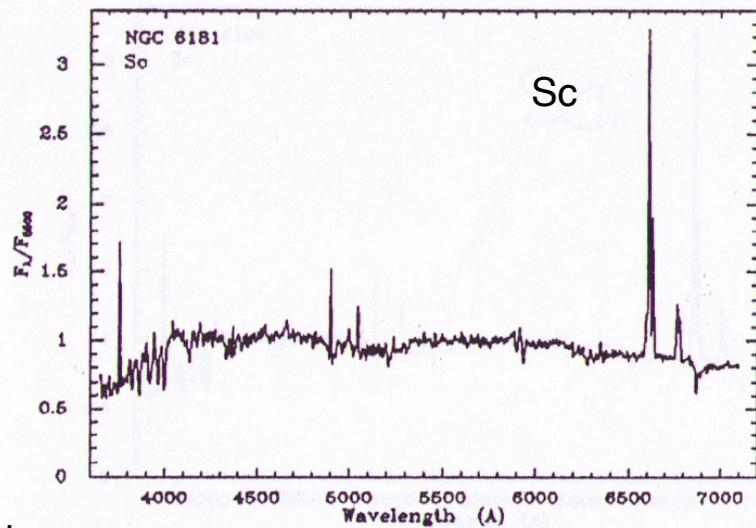
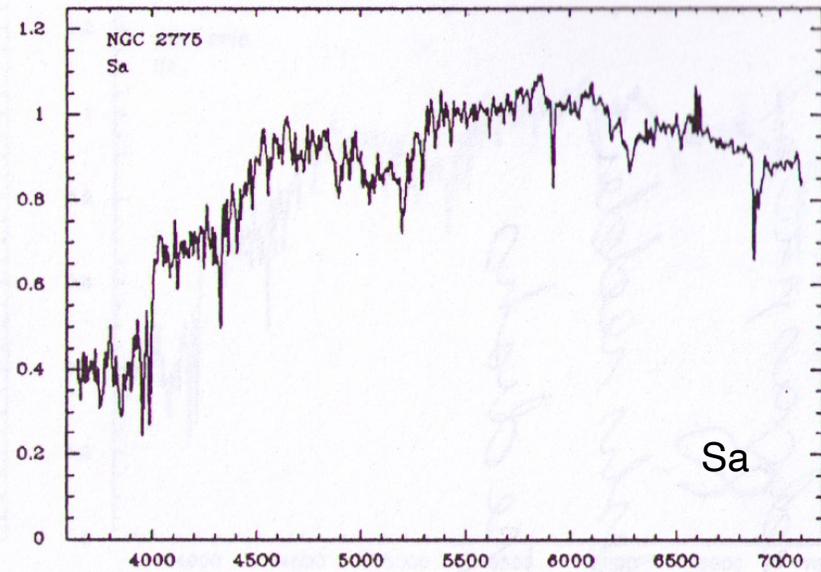
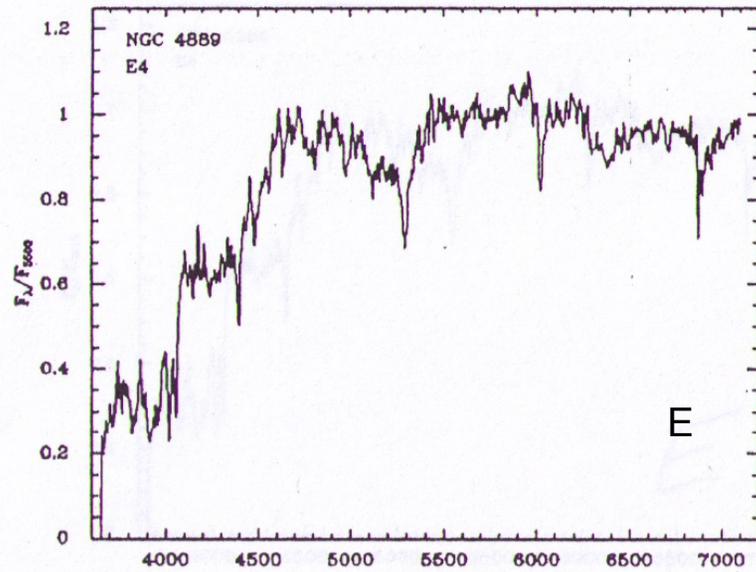
**TABLE 4.3** *Colors for different Hubble types*

<i>Type</i>	$(U-B)_0$	$(B-V)_0$	<i>Integrated spectral type</i>
E	0.50	0.92	K2
S0	0.48	0.92	K2
Sa	0.28	0.82	G9
Sb	0.27	0.81	G8
Sbc	-0.02	0.63	G2
Sc	-0.12	0.52	F8
Im	-0.20	0.50	F7

*Source:* de Vaucouleurs data, adapted from Vorontsov-Vel'yaminov 1987.

Thus, more massive, blue stars in late-type galaxies.

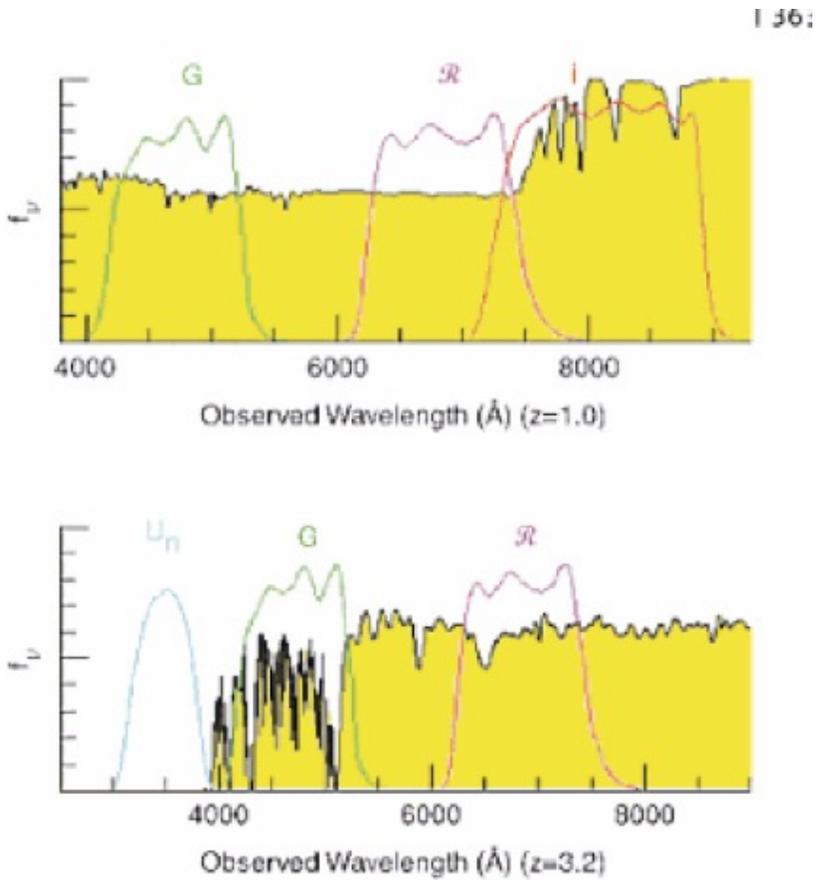
# Integrated spectra of E, S, and Irr (Kennicutt et al)



blue

red

# Dropouts



Schneider

Miley et al.

