PX269 Galaxies

Galileo (1609) 1st use of telescope in astronomy. Resolved Milky Way into "countless fixed stars".

Wright (1750s) realised Milky Way must be a disc of stars.

Kant suggested nebulae are "island universes"

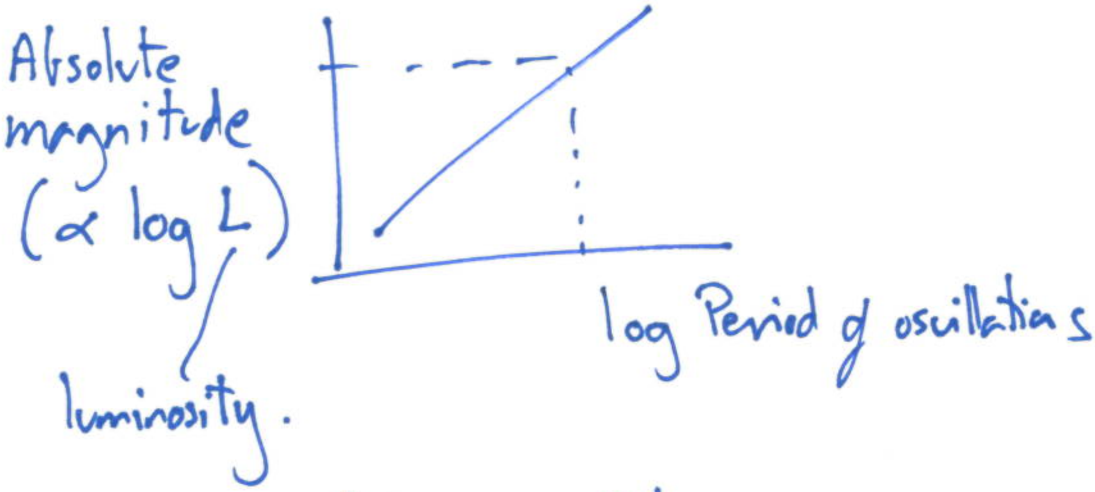
But there was no way to measure distance.

1800s many thousands of nebulae discovered, but no physical understanding.

Naming conventions e.g.

Andromeda $\equiv$ M31 $\equiv$ NGC 224

Hubble (1924) discovered individual Cepheid variable stars in M31. Cepheids known to standard candles, so distance can be determined.



Recall distance modulus

$$m - M = 5 \log_{10}(d) - 5$$

m: apparent mag.

M: absolute magnitude.

d: distance in parsecs.

For M31, $d = 770$ kpc

$= 2.3 \times 10^{23}$ m

$= 2.5 \times 10^{6}$ light years.

Proves galaxies external to Milky Way.

angular size & distance $\Rightarrow R \simeq 10$s kpc

For M31, $M = -20.8$ cf. $M_\odot = 5.48$

Recall

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{f_1}{f_2}\right)$$

m_1, m_2: apparent mags.

f_1, f_2: fluxes.

$$\Rightarrow \frac{f_{M31}}{f_{\odot}} = \frac{L_{M31}}{L_{\odot}} = 3\times 10^{10}$$

$$\Rightarrow L_{M31} = 3\times 10^{10} L_{\odot}$$

$\Rightarrow$ ~2×10^{11} stars in M31 (accounting for Sun being more luminous than average).

Hubble (1929) discovered the expansion of the Universe by plotting radial velocity (v_r) from Doppler shift of spectrum, against Cepheid distances.

component of velocity along our line of sight

$$\lambda_{obs} = \left(1 + \frac{v_r}{c}\right)\lambda_{em}$$

↑ observed wavelength

↑ emitted wavelength.

Hubble showed that

$$V_r = H_0 d$$

↑ Hubble's constant = 67.8 ± 0.8 km s^{-1} Mpc^{-1}

This implies a characteristic age for the Universe (assuming constant expansion)

$$\text{Hubble time} = \frac{1}{H_0} = 14 \text{ Gyr}$$

Also implies a characteristic size for observable Universe

$$\text{Hubble radius} = \frac{c}{H_0} = 4300 \text{ Mpc}$$

Previously known scale of the Universe was limited to Milky Way $\simeq 10$ kpc

So Hubble ↑ size of known Universe by $\times 10^6$!

Redshift (z) now commonly used as a proxy for distance

$$z = \frac{\Delta\lambda}{\lambda_{em}} \quad \text{or} \quad 1 + z = \frac{\lambda_{obs}}{\lambda_{em}}$$

for nearby galaxies $z \simeq \frac{v_r}{c}$

and so $cz \simeq H_0 d$.

14.7.1

Galaxy classification

3 main types:

Spirals, S

→ disc morphology, spiral structure, red bulges, blue discs, contain dust & gas

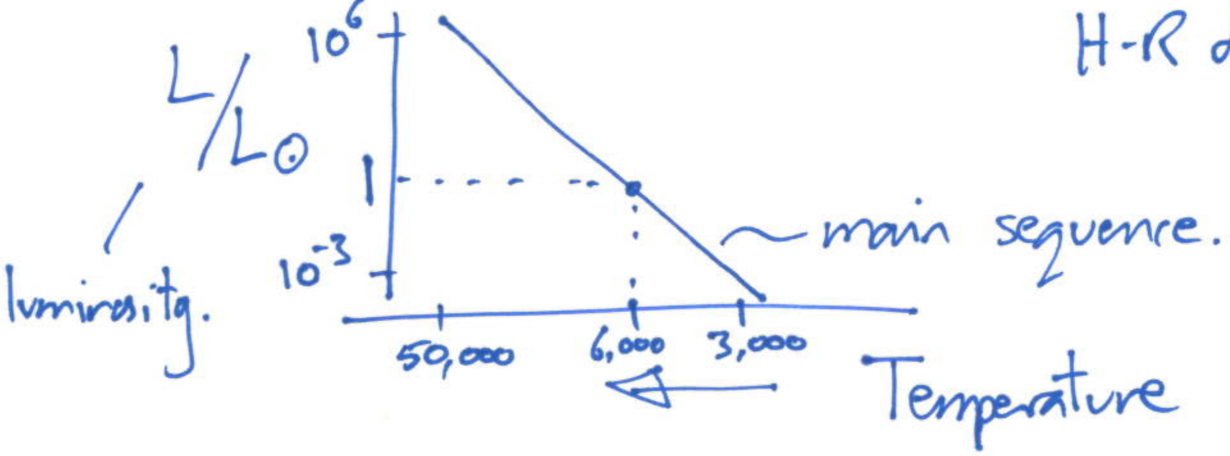
Ellipticals, E

→ elliptical morphology (triaxial spheroids), centrally condensed, red throughout, little gas & dust.

Irregulars, Ir

→ irregular morphology, flattened/disc-like, blue, usually without a bulge, less luminous than Ss.

Stellar populations



H-R diagram.

All masses of stars form together, but 14.2.2

$$L \propto m^3$$

L mass.

⇒ so massive, blue stars dominate the light from young populations.

Lifetime of main sequence stars:

$$\tau_{ms} \propto \frac{m}{L} \propto m^{-2}$$

L main-seq. lifetime

so massive stars die young.

⇒ old stellar populations are red.

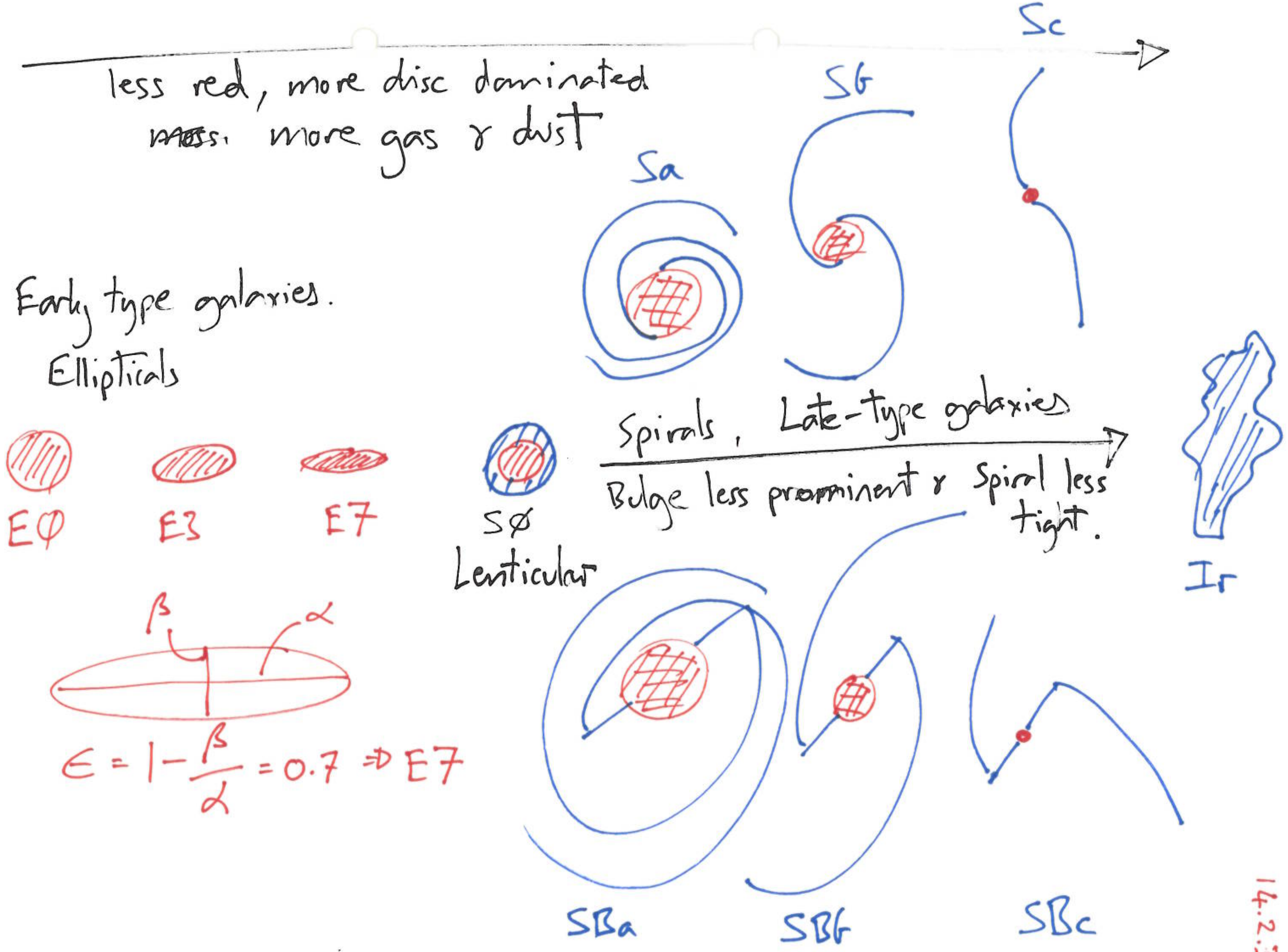
Colour/spectrum of a stellar population depends on the current star formation rate, and the star formation history.

determined by modelling the continuum emission as a population of different stellar types.

determined from the emission line strength of galaxy, as ionised gas recom lines.

~~Imp~~ Implies Ir & S are actively forming stars, whereas Es & spiral bulges are not. Consistent with the observed distn of gas & dust.

14.2.3



less red, more disc dominated
~~mass~~, more gas & dust

Early type galaxies.
Ellipticals

Spirals, Late-type galaxies

Bulge less prominent & Spiral less tight.

$$\epsilon = 1 - \frac{\beta}{\alpha} = 0.7 \Rightarrow E7$$

Elliptical classification:

Hubble scheme flawed for Es:

① depends on viewing angle,

② fails to reflect the large range of L.

faintest dSph - dwarf speroidal

$L \sim 10^{-4} L_*$

characteristic luminosity $\simeq L_{MW}$.

dE - dwarf ellipticals, $L \sim 10^{-2} L_*$

E/gE ellipticals & giant ellipticals

$L \sim L_*$

cD - central galaxies in clusters of galaxies $L \sim 25 L_*$

14.3.1

Spirals have a much narrower range of $L \simeq L_*$

But the spiral pattern is more pronounced in high L galaxies

⇒ Grand design spirals

lower L ⇒ weaker, fractured spiral

⇒ "flocculent" spirals

lowest L, spirals run into Ir galaxies.

Milky Way is an SBb/c galaxy.

14.3.2

Surface brightness

Unlike stars, galaxies are spatially resolved, so surface brightness is key to detection.

Measure mean surface brightness within, R_e,

effective radius
$\equiv$ half-light radius

$$\Sigma = \frac{L\,\text{[illegible]}}{2\pi R_e^2} \simeq \frac{3\times 10^{10} L_\odot}{2\pi\,(10\,\text{kpc})^2}$$

$$= \underline{50\, L_\odot\, \text{pc}^{-2}}$$

Note: galaxies are optically thin, so surface brightness is luminosity integrated along our line of sight.

In magnitudes

$$\mu - M = 5\log_{10}\left(\frac{\text{size}}{10\text{pc}}\right) \text{ mag radian}^{-2}$$

absolute magnitude

surface brightness.

in mag arcsec^{-2}

$$\mu - M = 5 \log_{10}\left(\frac{\text{size}}{10\text{pc}} \times \frac{360 \times 60 \times 60}{2\pi}\right)$$

$$= 5 \log_{10}\left(20626 \times \text{size (pc)}\right)$$

For a typical E/S with $\sim 100 L_\odot \, \text{pc}^{-2}$

$$\Rightarrow \mu = 22 \text{ mag arcsec}^{-2}$$

This is faint. Approx the brightness of the night sky from a good site.

So detecting low surface brightness galaxies (LSBGs) e.g. dSph, is very challenging. Only possible recently, surveys are very incomplete, even very locally.

Note: surface brightness doesn't depend on distance (at low z) because the decrease in total brightness with distance cancels w. the apparent size of galaxy.

14.3.4

Typical values of R_e

E_s/S_s $\quad R_e \sim 10\,\text{kpc}$

cD $\quad R_e \sim 100\,\text{kpc}$

$dE/dSph$ $\quad \sim 200\,\text{pc}$

Note, although dE/dSph are small, they are less compact than cD/gE/Es

⇒ 2 distinct classes of E galaxy.

Surface brightness profiles, $\mu(R)$

Spiral discs & dE/dSph have exponential profiles

$$I(R) = I_0 \exp\left(-\frac{R}{a}\right)$$

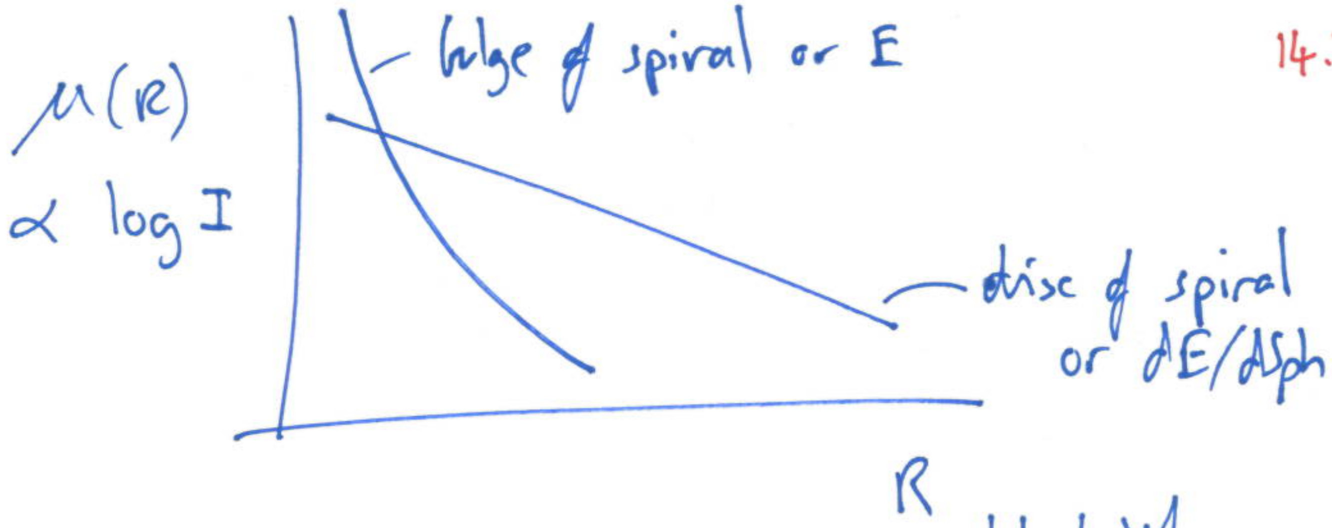
↑ intensity ↑ scale length.

In contrast, Es and bulges of Ss have a steeper function : "de Vaucoulers law" or "$R^{1/4}$" law.

$$I(R) = I_0 \exp\left(-\left(\frac{R}{a}\right)^{1/4}\right)$$

in both cases I drops by $1/e$ at $R = a$

14.3.5



$\Rightarrow$ Ss/Es are much easier to detect than dE/dSphs.

Total luminosity from integrating the profile

$$L(<R_{max}) = \int_0^{R_{max}} I(R)\, \underbrace{2\pi R . dR}_{\text{area of annulus at } R}$$

for exponential profile

$$= 2\pi a^2 I_0 \left(1-(1+x)e^{-x}\right)$$

where $x = \frac{R_{max}}{a}$

as $R_{max} \to \infty$

$$\underline{\underline{L_{total} = 2\pi a^2 I_0}}$$

so by assuming exponential continues beyond detection limit, can estimate L_{tot}

only by studying inner regions.

Also measure R_e

$$\tfrac{1}{2} = (1+x)e^{-x} \Rightarrow x = 1.69 = \frac{R_e}{a}$$

$$\Rightarrow \underline{\underline{R_e = 1.69\,a}}$$

So in practice can measure R_e by fitting the surface brightness profile for a, even if only the inner galaxy is detectable.

For Es and spiral bulges, integrating the $R^{1/4}$ law,

$$L_{Tot} = 8!\,\pi a^2 I_0$$

$$R_e = 3461\,a$$

For S galaxies (both components)

$$\frac{L_{Bulge}}{L_{Disc}} = \frac{8!\,\pi a_B^2 I_{0,B}}{2\pi a_D^2 I_{0,D}}$$

$$= 1 \rightarrow 0.1$$

in terms of Hubble sequence   S0   Sd

Luminosity function ≡ number density of galaxies vs. luminosity.

Difficult to measure because of selection against LSBGs (eg. dE / dSph) but important in telling us where most stars are in universe, and also as input to models of galaxy formation & evolution.

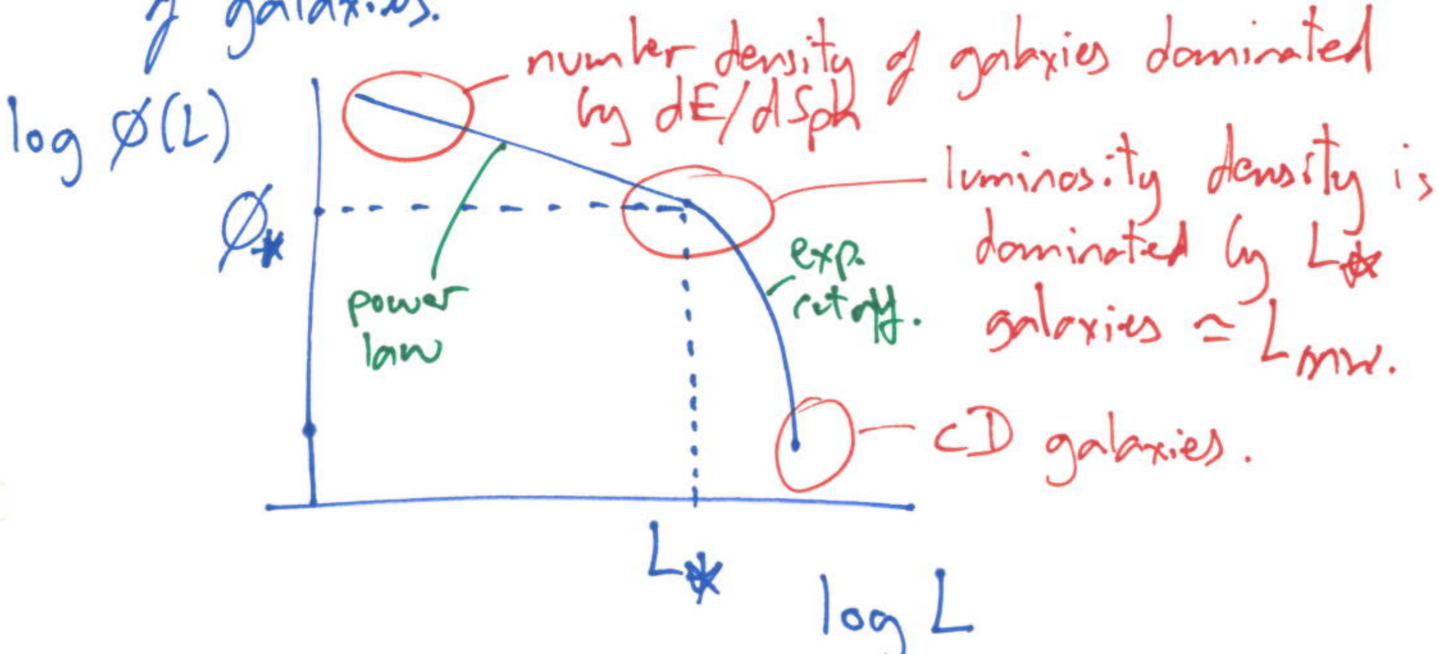
observed distribution is dominated by low luminosity galaxies (power law) with a steep cut off at high luminosity (exponential).

Schechter function

$$\phi(L) = \frac{\phi_*}{L_*} e^{-L/L_*} \left(\frac{L}{L_*}\right)^{\alpha}$$

number density of galaxies.

normalisation constants.



From fitting the observed distribution

$L_* \simeq 2\times10^{10} L_\odot \simeq L_{mw}$.

ϕ_* - the number density of L_*-galaxies.
$\simeq 0.0055\ Mpc^{-3}$

14.4.3

Estimate the total luminosity density of the Universe by integrating the Schechter ftn.

$$\mathcal{L} = \int_0^\infty \phi(L)\, L\, dL$$

$\mathcal{L}$ luminosity density.

$$= \frac{\phi_*}{L_*} \int_0^\infty L\, e^{-L/L_*} \left(\frac{L}{L_*}\right)^\alpha dL$$

measured $\alpha \simeq -1.2$

setting $\alpha = -1$

$$\simeq \phi_* L_*$$

So total luminosity density must be dominated by L_* galaxies.

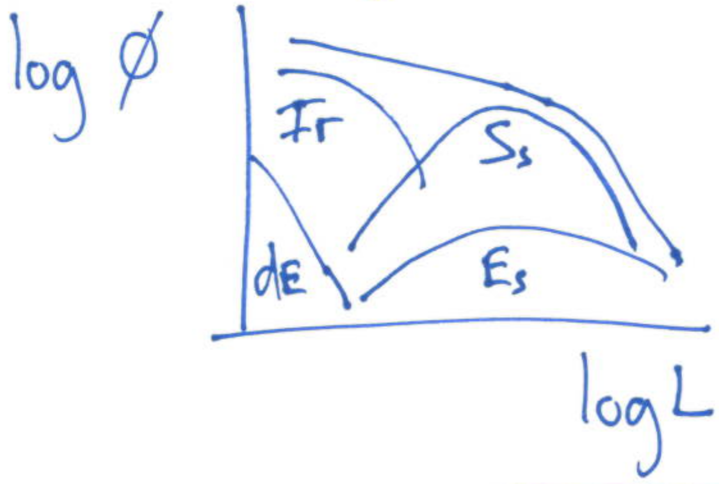
Total number ~~of~~ density of galaxies.

$$n = \int_0^\infty \phi(L)\, dL = \infty$$

So in practice the luminosity function must truncate or turn over, but this is beyond current detection levels.

14.4.4

Real luminosity functions for local universe



Part 2 Spiral galaxies

Disc is blue (young) stellar population ≡ Population I

Bulge is red (old) stellar population ≡ Population II

Spiral arms have the bluest/youngest stars
⇒ site of current star formation.

due to gravitational collapse of gas compressed as it passes through the spiral arms, which are sound waves in the gas disc.

Discs are flattened by a factor ~ 10

Vertical structure is also an exponential, so 3d structure of a spiral disc.