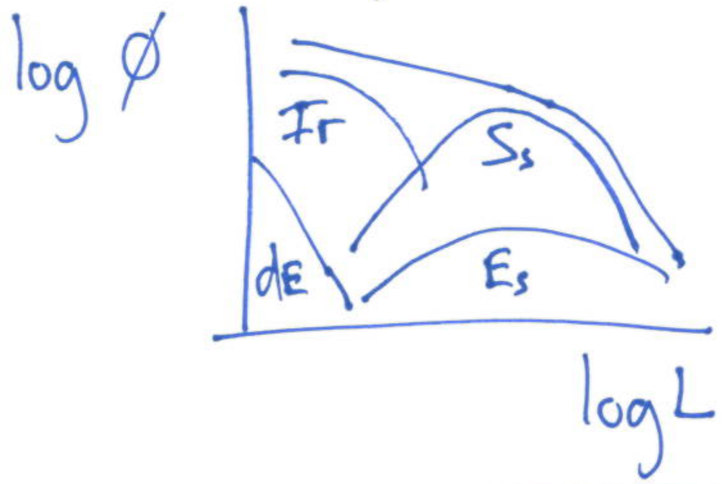
Real luminosity functions for local universe



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
$\Rightarrow$ 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.

(in cylindrical polar co-ords)

$$\rho(R, z) = \rho_0 \exp\left(-R/a\right) \exp\left(-\frac{|z|}{h}\right)$$

height above disc

scale length

scale height.

so typically $h \sim \frac{a}{10} \sim$ few 100 pcs.

Our Galaxy

Note: "our Galaxy" / "a galaxy"

→ 1st attempt to map our Galaxy by Herschel, 1785, by counting stars in different directions
⇒ Sun close to centre; complex shape.

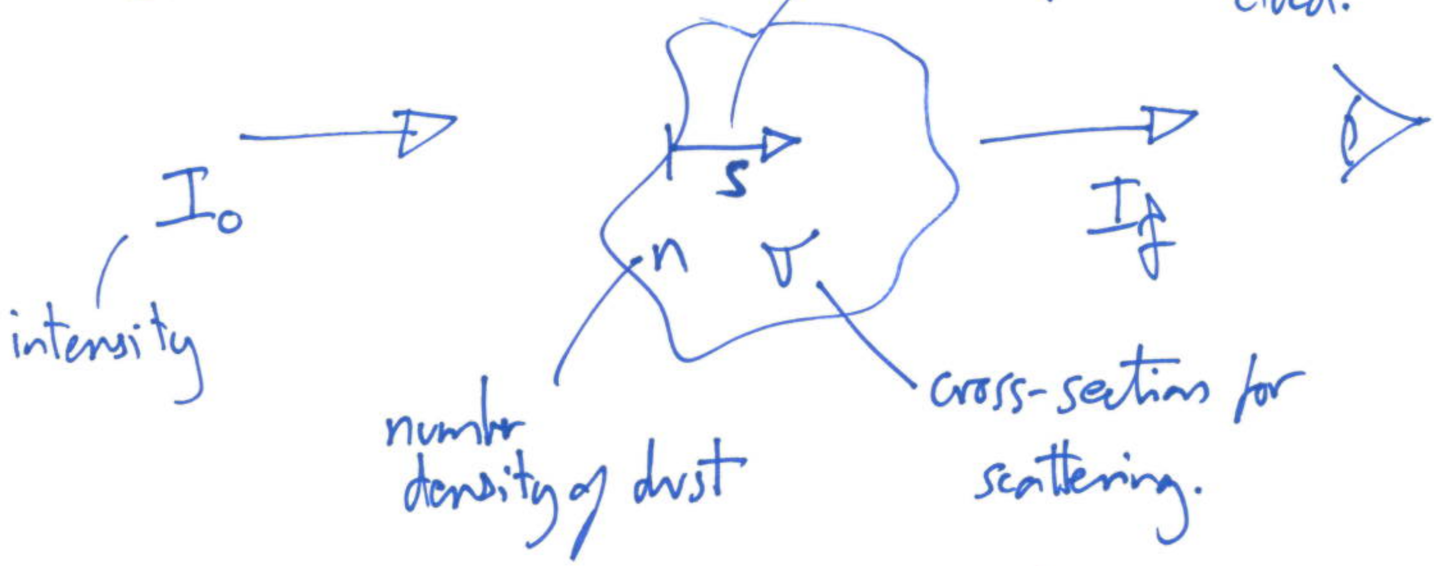
→ Star counts combined with distances from H-R diagram, still puts the Sun close to centre (650pc from centre) with $R \sim 10kpc$
(Kapteyn, 1922)

→ Shapley, 1919 noted that all the globular clusters are on one side of sky
⇒ Sun not at centre of the Galaxy.
Distance scale from pulsating stars in globular clusters ⇒ $R \sim 100kpc$ $R_{\odot} \sim 20kpc$.

Discrepency due to dust extinction in the interstellar medium (ISM)

→ caused Kapteyn to under-count distant stars.
→ caused Shapley to over-estimate distances to G.C.s due to extinction to calibrator stars in the Galactic Plane.

Dust extinction



Fractional decrease in intensity.

$$\frac{dI}{I} = -n\sigma\, ds$$

Total effect by integrating:

$$\int_{I_0}^{I_f} \frac{1}{I}\, dI = -\sigma \int_0^S n(s)\, ds$$

assume $n = \text{constant}$

$$\Rightarrow \quad I_f = I_0 \exp\big(-\underbrace{n\sigma s}_{}\big)$$

$\hookrightarrow \tau \equiv$ optical depth of cloud

Distance modulus

$$m - M = 5\log_{10}\left(\frac{d}{10\text{pc}}\right) - A$$

$\uparrow$ dust extinction.

$$A = \underbrace{m_f - m_0}_{\text{change in apparent mag. due to extinction}} = -2.5 \log_{10}\left(\frac{I_f}{I_0}\right)$$

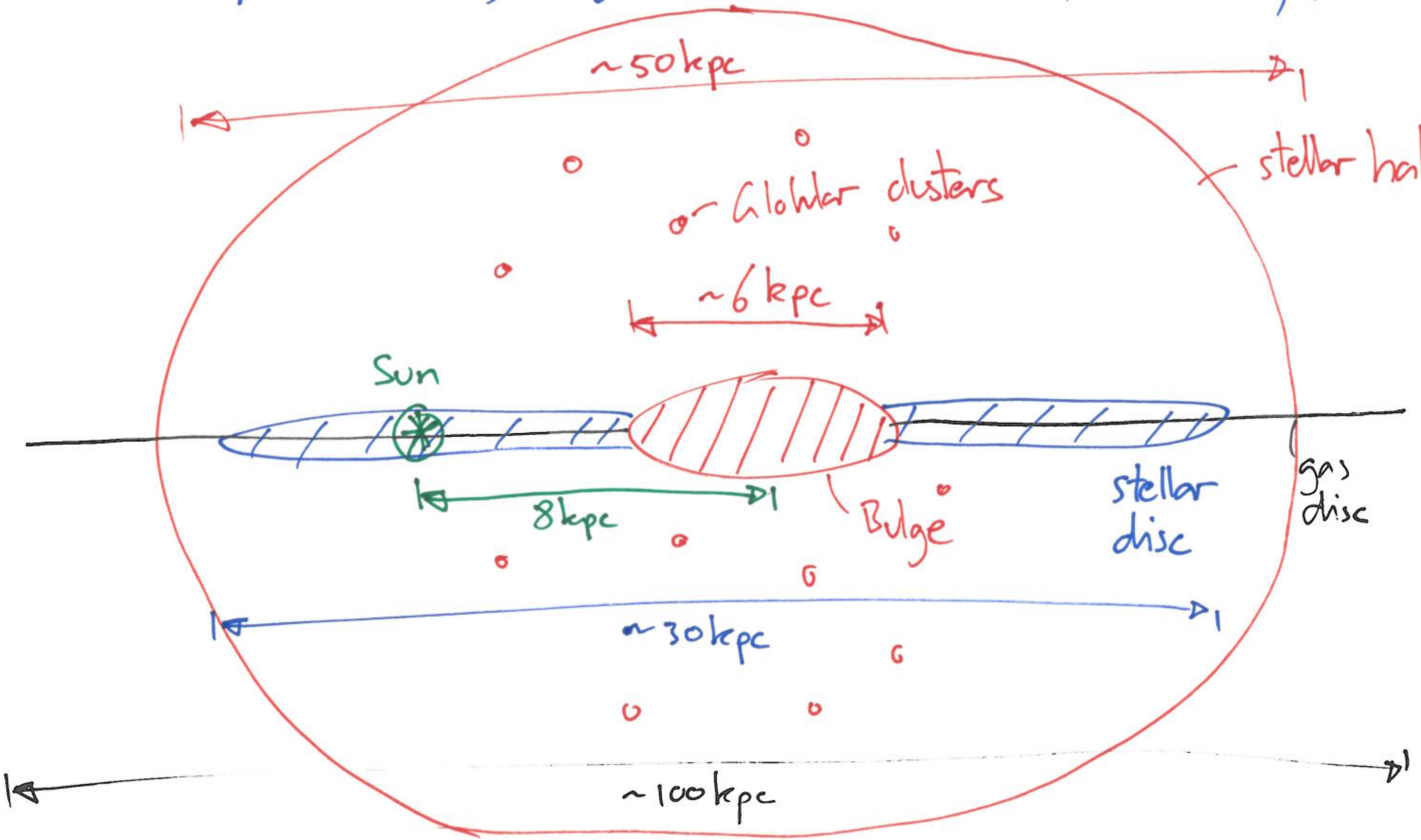
$$= -2.5 \log_{10}\left(e^{-\tau}\right)$$

$$= 1.09\,\tau$$

useful to remember $A \simeq \tau$

Typically in Galactic plane $A \simeq 1\,\text{mag}/\text{kpc}$

In practice dust extinction can be estimated by the λ-dependence of the cross-section. (dust extinction is often called reddening) structure of the Milky Way based on star counts, accounting for extinction.



14.5.4

Stellar components

Population I: thin disc, $h \sim 300\,pc$
$a \sim 2\,kpc$

Note: h is different for different spectral types.

hotter & more massive & lower & younger $\downarrow$

K stars, $h \sim 350\,pc$
A ", $h \sim 200\,pc$
OB ", $h \sim 100\,pc$

$\Rightarrow$ short-lived stars found closer to Galactic Plane $\Rightarrow$ stars form in G.P., move to higher average scale heights as their orbits evolve through scattering with other stars.

Population II:

$\rightarrow$ Galactic / ~~stellar~~ stellar halo
$\sim$ spherical, $\rho \propto R^{-3}$
mainly v. old stars
very low metallicity $\lesssim 10^{-2}$ Solar
fraction of material not H or He

stars form from the ISM, which initially is only H & He, but is polluted over time by heavier elements formed in stars & returned to ISM ~~by~~ when stars die.

So metallicity depends on the star formation history of the region of formation.

→ G. halo is now thought to be debris from dwarf galaxies that have been tidally disrupted and accreted by the Milky Way.

~~th~~ Galactic bulge:

→ Globular clusters, v. old stars $\simeq 12$ Gyrs from modeling the H-R diagram for each cluster. (cf. Universe ~ 13.7 Gyr old).

metallicity $\sim 10^{-2}$ Solar.

→ G.C.s thought to have formed early in the history of the M.W. – early in the gravitational collapse of the primordial gas cloud.

→ **Galactic bulge**: v. old stars. metallicity $\simeq 0.5$ Solar

Also, $h \sim 400pc$ (still a disc-like/flattened object, unlike the Halo/distn of G.C.s).

→ indication of intense star formation in the centre of the early galaxy (with SNe polluting the ISM).

→ **thick disc**: old stars with $h \sim 1350pc$

controvertial whether this is part of the disc or a flattened part of the halo.

By stellar mass: thin disc $\sim 10^{11} M_\odot$
Bulge $\sim 10^{10} M_\odot$
Halo $\sim 10^{9} M_\odot$

by modelling the luminosity & colour of the stellar population.

By numbers in the Solar neighbourhood:

$\sim 98\%$ thin disc

$\sim 2\%$ thick disc

$\sim 0.1\%$ halo

Sun is at $z \simeq 15pc$
↑ height above Galactic Plane.

$V_z = 7\,kms^{-1}$ toward North Galactic Pole.

Non-stellar components

$\Rightarrow$ gas
$\Rightarrow$ dust $\Big\}$ ISM
$\Rightarrow$ dark matter

By mass H ~ 70%
28% He
2% metals.

H gas ~~exists~~ in 3 forms:

molecular, H_2
~~atomic~~ Atomic, HI
ionised , HII

HII is the most visible because it emits strong recombination emission lines

$\Rightarrow$ dominates the line emission of galaxies.

Ionisation potential of H is $13.6\,eV \simeq 2.2\times10^{-18}\,J$

so to photoionise, we need photons of

$$\lambda \leq \frac{hc}{2\times10^{-18}J} = \underline{91\,nm}.$$

far ultraviolet.

Recall, Wein displacement law for B.B. emission,

$$\lambda_p T = 0.0029\,m\,K$$

peak λ of B.B.

set $\lambda = 91\text{nm}$ $\Rightarrow$ $T \sim 30{,}000\,K$

so only the hottest stars can produce large quantities of photons to ionise the ISM.

So only see HII regions around the hottest, youngest stars (OB stars)

$\Rightarrow$ emission lines are a powerful tracer of current star formation.

Studies at low z show where stars form in galaxies (in spiral arms)

Studies at high z attempt to trace the star formation history of the Universe.

---

size of an HII region by assuming eqm between ionisation & recombination

$$\underbrace{N}_{\text{ionisation rate}} \simeq \frac{L_{UV}}{13.6\text{eV}} = \underbrace{\frac{4}{3}\pi r_s^3}_{\substack{\text{volume of}\\ \text{HII region}}} \underbrace{n_e n_p}_{\substack{\text{number densities}\\ \text{of } e^- \, p^+\text{s}}} \alpha^{\text{recom. coeff.}}$$

assume $n_e = n_p = n_H$

$$\Rightarrow r_s = \left(\frac{3N}{4\pi\alpha}\right)^{1/3} n_H^{-2/3}$$

$\Rightarrow$ measure n_H from HII

$\simeq$ few pc around

an OB star.

14.6.5

Strongren radius.

HI has high excitation potential,

$n=1 \rightarrow n=2$ is 10eV

so we don't see emission lines, except in HII regions.

Fortunately HI has a unique transition in the radio spectrum, due to hyper-fine splitting of ground state,

$$\uparrow p^+ e^- \uparrow \longrightarrow \uparrow p^+ e^- \downarrow$$

aligned spins

$$\Delta E = 10^{-24} J = 10^{-5} eV$$

$$\Rightarrow \lambda = 21cm$$

$$f = 1.4 \, GHz.$$

Extremely useful for tracing HI gas, because collisionally excited even at v. low temperatures.

$$\Delta E \simeq \overline{K.E.} = \tfrac{3}{2} kT$$

$$\Rightarrow T \geqslant 0.05K \text{ is sufficient.}$$

Typically ISM, $T \sim 100K$, whole universe $\sim 3K$

$\Rightarrow$ 21cm line emitted by all the HI in Universe!

mapping the 21cm line in M.W. & nearby galaxies

⇒ HI confined to disc of spirals, $h \sim 100$pc

⇒ Extends well beyond the stellar disc

⇒ almost entirely absent in bulge and in elliptical galaxies.

⇒ Believed the galaxies accrete HI gas from the intergalactic medium (IGM), infall into the centre of galaxies is halted by cons. of ang. momentum, disc ~~is the~~ with circular orbits is lowest energy configuration for specific ang. mom. distn.

Another v. useful feature is that 21cm transition is highly forbidden, ⇒ $\tau = 4 \times 10^{14}$ s $\simeq$ 10 million years!

timescale for deexcitation.

⇒ emission is v. weak, but absorption also weak ⇒ most of M.W. is transparent.

⇒ map M.W. structure.

Also allows us to measure total mass in HI

$\simeq 10^{10} M_\odot$

$\simeq 10\%$ stellar mass of the disc.

but $\bar{n}_H = \dfrac{N_{tot}}{\text{Volume}} = \dfrac{10^{10} M_\odot / m_H}{\pi R^2 h}$

mean number density of H

Take $R \sim 30\,\text{kpc}$, $h \sim 100\,\text{pc}$

$\Rightarrow \bar{n}_H \simeq 1\,\text{cm}^{-3}$

H_2 is almost impossible to detect, lack of emission transitions.

In practice molecular gas is traced ~~by~~ via the vibrational transitions of asymmetric molecules esp. CO, which is relatively abundant, & has transitions at ~~λ~~ $\lambda = 1.3\,\text{mm}$ & $2.6\,\text{mm}$.

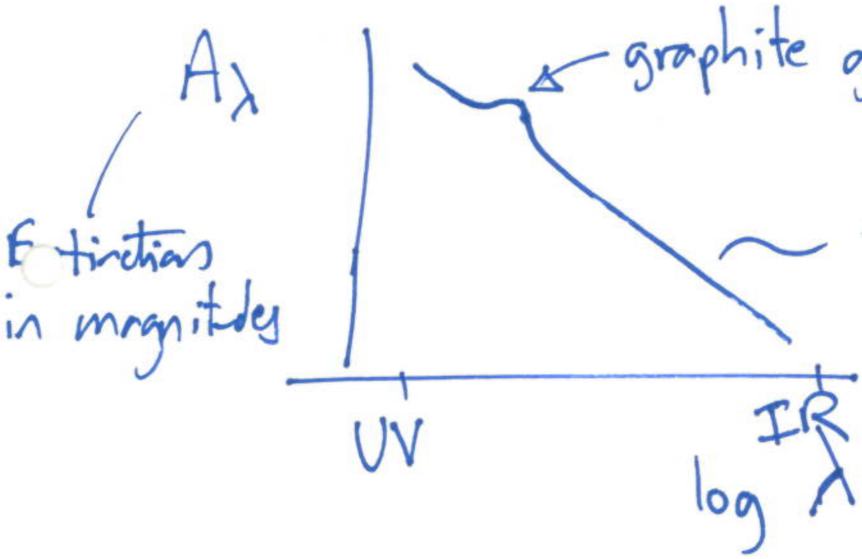
Mapping results $\Rightarrow$ mol. gas confined to small, cold, dense regions in disc $\rightarrow$ molecular clouds

typically $R \sim 10 - 100\,\text{pc}$, $\rho \sim 10^3$ typical ISM.

Grav. collapse of mol. clouds in spiral arm density waves that forms stars.

⇒ find HII regions form at margins of mol. clouds, e.g. Orion nebula.

<u>Dust</u> Extinction is stronger in blue than red.



$\sim \tau_\lambda \propto \sigma_\lambda \propto \frac{1}{\lambda}$

This slope across UV - optical - IR is characteristic of scattering, specifically Mie scattering, occurs when $R_g \simeq \lambda$

grain size

⇒ dust scattering.

$R_g \simeq 0.01 - 1 \mu m$ ≃ smoke particles

cf $R_g \gg \lambda$ ⇒ σ independent of λ

$R_g \ll \lambda$ ⇒ Rayleigh scattering. $\sigma \propto \frac{1}{\lambda^4}$

14.7.5

molecular absorption features from detailed spectroscopy

→ mostly silicates (rock)

→ often coated in ices of volatiles, (eg. H_2O, CO, NH_3, CH_4).

14.8.0

Dust condenses in cold dense environments

→ molecular clouds

→ outflows from red giant stars.

Note: because of reddening by dust, it is best to use IR for studies of galaxy structure.

At longer λ's in mid-to-far IR the dust is seen in emission, heated by surrounding stars.

Star formation rate indicators

1) UV light from young massive stars (seen in the optical or IR at high z).

2) Emission lines from HII regions, (powered also by the UV emission of young stars).
At low ~~z~~ z, we because reprocessing UV light into visible light.
At high z, can detect the v. strong Lyα line ($n=2 \to n=1$) even when the star light continuum is undetectable.

3) Strong far-IR emission from dust heated by obscured massive stars

Seen even when the star formation regions are completely hidden by dust.

recall, $L_{BB} = A\sigma T^4$

luminosity high because area of dust grains is high.

Studies of star formation show a small fraction of galaxies w. v. high star formation rates ⇒ distinct episodes of star formation in the history of ~~ex~~ each galaxy.

2 types of star forming galaxies:

→ Starburst galaxies

- galaxies with strong 1) + 2).

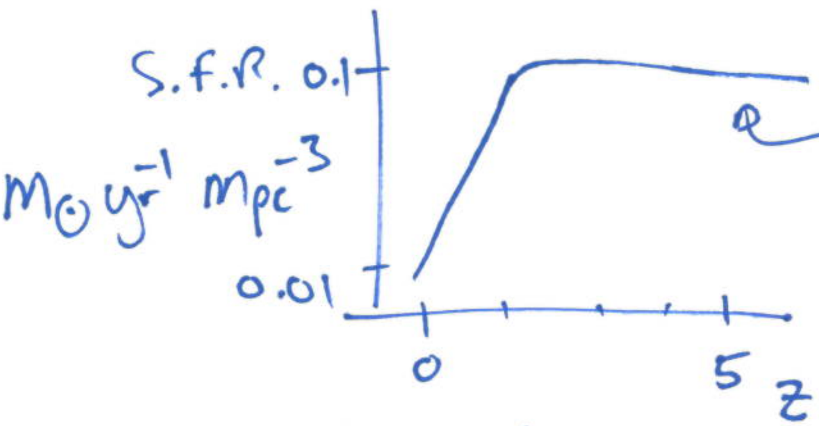
⇒ un-obscured star formation

→ Ultra-luminous infra-red galaxies

ULIRGs

- galaxies w. strong 3).

Galaxy surveys trace star formation over cosmic history ⇒ Madau plot.



less certain due to extinction and incompleteness of surveys.

Crucial input to galaxy formation models.

14.8.3

Kinematics of spiral galaxies

How do the stars orbit?

→ in a disc. in a coherent rotation?
or random directions? or highly eccentric?

Use Doppler effect to probe kinematics, measure the radial velocity. vs radius
(V_r - component of velocity along our line of sight.)

Recall $$\frac{\Delta\lambda}{\lambda} \simeq \frac{V_r}{c}$$

need to correct velocity for the inclination of the galaxy.

$$V_r = V \sin i$$

estimate i by assuming disc is circular and comparing semi-major & semi-minor axes

i.e. $b = a \cos i$

Use long-slit spectroscopy to measure the Doppler shift of emission lines from HII regions in disc, along the semi-major axis.

Results ⇒ disc does rotate coherently, systematic shift from one side of the galaxy to the other.

⇒ bulge shows broadening of absorption lines from the many stars,

⇒ stars orbits are randomly orientated.

Useful to think of stars as particles in collisionless gas.

Disc ⇒ cold gas, supported against gravity by rotation.

Bulge ⇒ hot gas, pressure supported against gravity.

Can use rotational velocities to measure mass of galaxy.

cf. Solar system - circular orbits around a point mass.

equate centripetal force & grav. force.

planet mass — mass of sun

$$\frac{\cancel{m_p} V^2}{r} = \frac{G M_\odot \cancel{m_p}}{r^2}$$

orbital separation

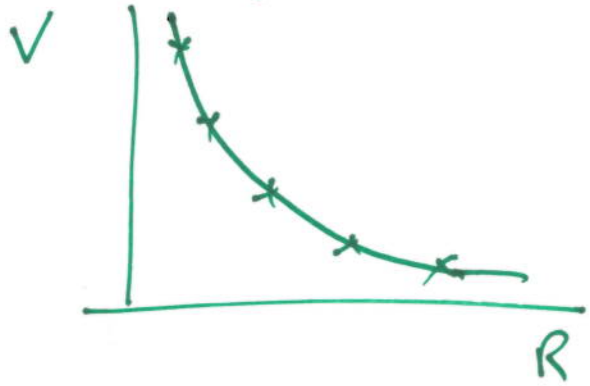
$$\Rightarrow M_\odot = \frac{V^2 r}{G}$$

For Earth, $V = \frac{2\pi \, 1\,AU}{1\,yr} = 30\,km\,s^{-1}$

$$\Rightarrow M_\odot = 2 \times 10^{30}\,kg.$$

Recall, $M_\odot = \frac{V^2 R}{G}$

Rotation curve of Solar system.



$V \propto R^{-1/2}$

Galaxies more complex because mass is not concentrated at the centre,

<u>But</u> Gauss's theorem, general property of vector fields.

$$\underbrace{\oint_S \underline{F} \cdot ds}_{\text{surface integral of field}} = \underbrace{\int_V \underline{\nabla} \cdot \underline{F} \, dv}_{\text{volume integral of divergence of field.}}$$

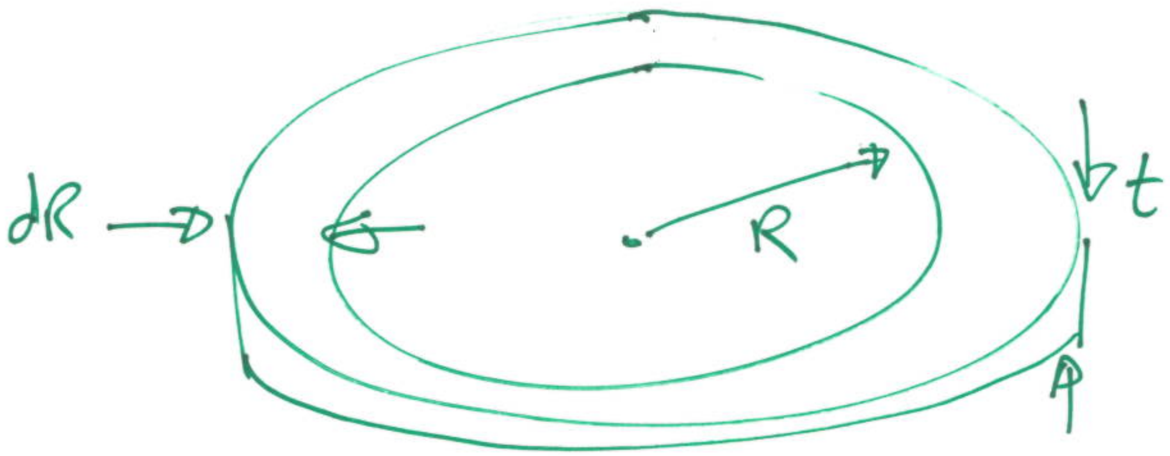
For, gravitational field divergence is mass.

$$\Rightarrow \underbrace{M(<R)}_{\text{mass enclosed by the orbit.}} = \frac{v^2 R}{G}$$

Only strictly true for spherically symmetric mass distn.

consider $\rho(R)$, by assuming a 3D mass distn.

(1) assume all mass in the disc



Volume of annulus, $dV = 2\pi R t\, dR$

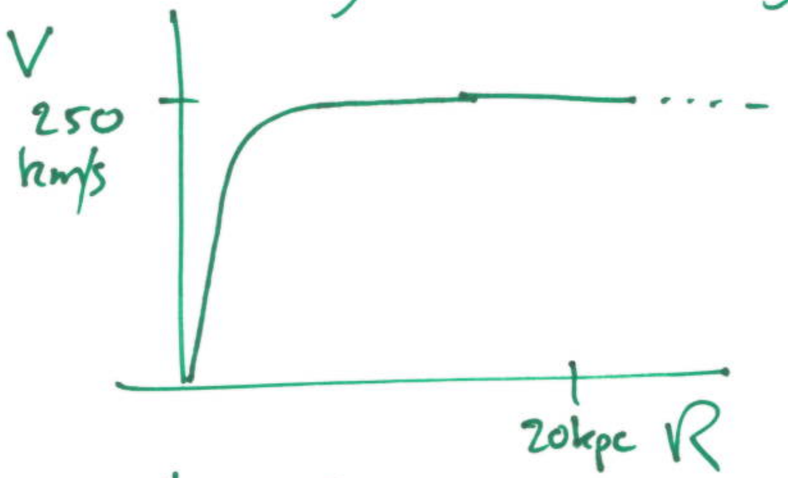
mass of annulus, $dM = \rho 2\pi R t\, dR$

$$\Rightarrow \frac{dM}{dR} = 2\pi R t \rho = \frac{v^2}{G}$$

$$\Rightarrow \rho(R) = \frac{V(R)^2}{2\pi t R G} \propto \frac{1}{R}$$

14.9.3

Observed rotation curves of spiral galaxies rise steeply in centre, as more mass is enclosed, then stay flat to large radii



(should have done this before $\rho(R)$, and talked about implication for $M(R)$.)

If mass is all in disc (which is expected if stars dominate mass), then $\rho(R) \propto \frac{1}{R}$

Recall, the brightness profile of galaxy discs $\propto e^{(-R/a)}$ which traces the stars.

$\Rightarrow$ stars do not account for the dominant mass of a galaxy.

$\Rightarrow$ Galaxies dominated by Dark Matter!

For a typical spiral galaxy, $V \sim 250\,\text{km s}^{-1}$
at $R \sim 20\,\text{kpc}$

$$\Rightarrow M(<20\,\text{kpc}) = 6 \times 10^{41}\,\text{kg}.$$
$$= 3 \times 10^{11} M_\odot.$$

Consider mass to light ratio : $\frac{\text{Mass}}{\text{Luminosity}}$ $\frac{M_\odot}{L_\odot}$

typically for discs of spirals.

$$\frac{M}{L} \sim 5 \frac{M_\odot}{L_\odot}$$

measurements at largest radii, e.g. from the orbits of dwarf galaxies

$$\frac{M}{L} \sim 50 \; !$$

---

(2) Exercise: show that spherically distributed mass must have density profile of

$$\rho(R) = \frac{V^2}{4\pi G R^2} \propto \frac{1}{R^2}$$

14.9.5

Kinematics of the Milky Way

Difficult to measure from our location within the galaxy, and due to dust extinction.

But for nearby stars we can measure the 3D velocity,

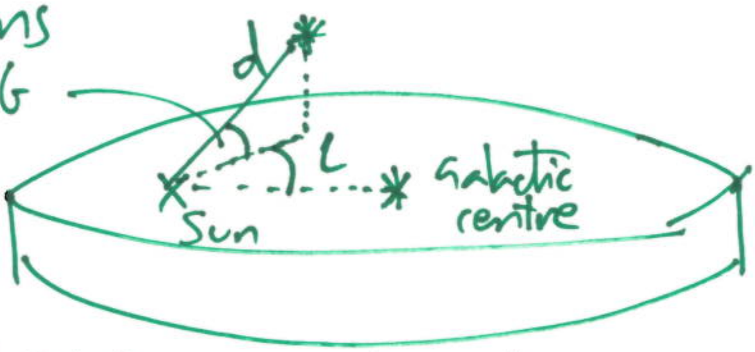
v_r from Doppler shift

also v_t, transverse velocity from proper motion, which is the angular velocity on the sky.

$$\mu = \frac{d\theta}{dt} = \frac{v_t}{d}$$

---

positions

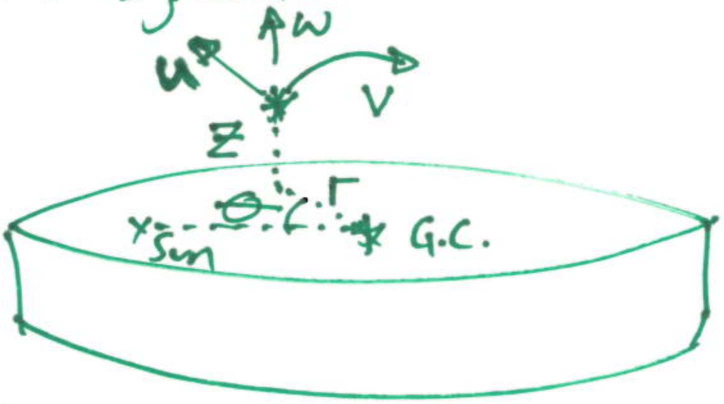


Galactic co-ordinates.

$l \equiv$ ~~gal~~ Galactic longitude, $b \equiv$ Galactic latitude

d = distance. — includes all of the uncertainties

For kinematics, easier to use a Galaxy-centred co-ordinate system.
14.9.6 + 14.10.0



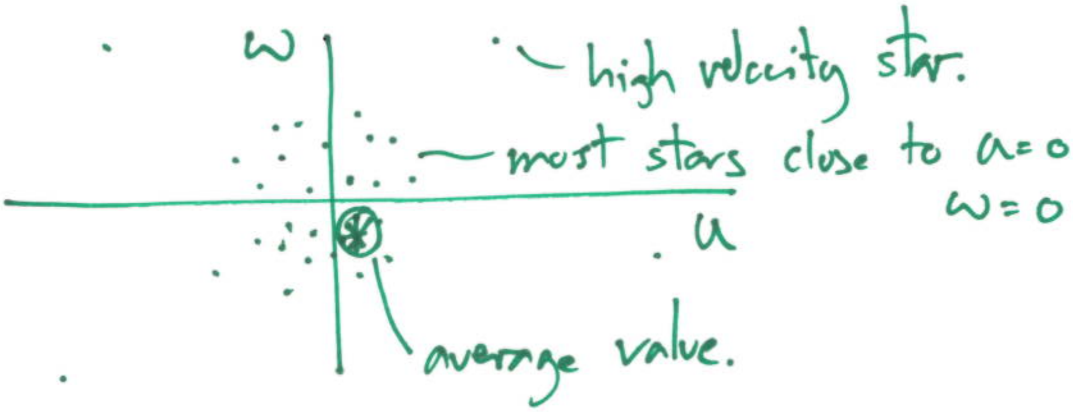
position (r, θ, z)

velocity (u, v, w) measured wrt the local standard of rest, which is an idealised Solar orbit.

(orbit the Sun would have, if perfectly circular & in the plane of the galaxy.

14.10.0

For v. nearby stars can measure 3D velocity, so we know u, v, w wrt the LSR.

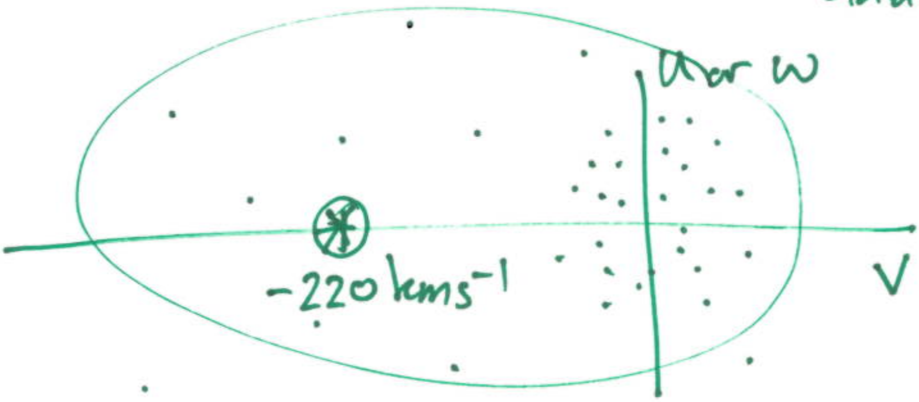


14.10.1

Assume the Galaxy is stable

$\Rightarrow \quad u_\odot = -\bar{u} = -9 \text{ kms}^{-1}$ — we are moving towards Gal. Centre

$w_\odot = -\bar{w} = 7 \text{ kms}^{-1}$ — towards North Galactic pole.



high velocity stars

High velocity stars are halo stars passing through the disc, not orbiting the Galaxy with the disc. Assume halo has negligible net rotation

$$-\bar{V}_{halo} = V_{LSR} = \underline{220 \text{ kms}^{-1}}$$

Recall, $M(<R) = \dfrac{V^2 R}{G}$

$V_\odot \simeq 220 \text{ kms}^{-1} \quad R_\odot \simeq 8 \text{ kpc}$ — e.g. by measuring the average distance to globular clusters.

distance of Sun from G.C.

$$\Rightarrow M_{MW}(<R_\odot) = 1.7 \times 10^{41} \text{ kg}$$
$$= \underline{9 \times 10^{10} M_\odot}$$

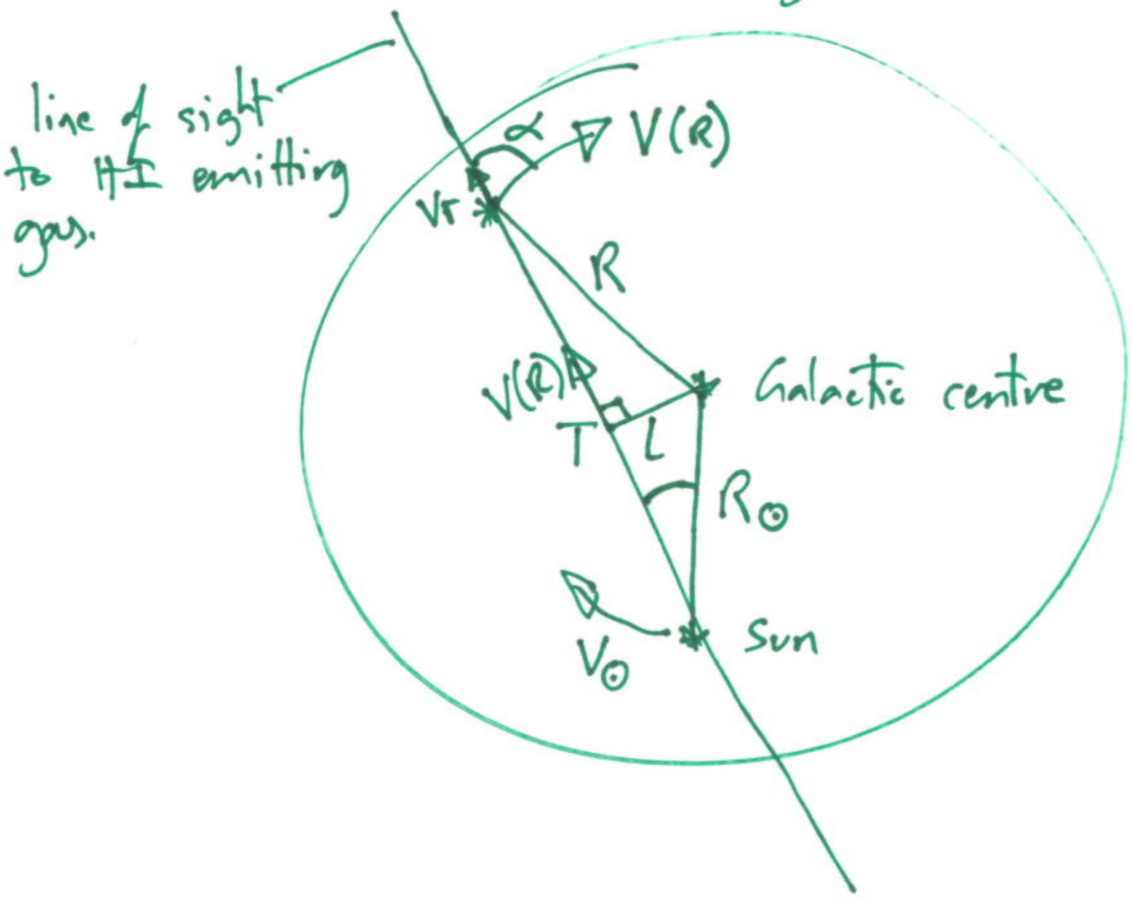
14.10.2

Note $$P_\odot = \frac{2\pi R_\odot}{V_\odot} = \underline{220\ \mathrm{Myr}}.$$

We want to measure the rotation curve of the Milky Way.

→ need velocities at large distances
⇒ V_r but not V_t

→ also need to see through the dust in the Galactic plane. ⇒ use the 21cm of HI. Doppler shift of line → V_r also visible at large distances.



$$V_r = \underbrace{V(R)\cos\alpha}_{\text{component of gas cloud velocity along our line of sight.}} - \underbrace{V(R_\odot)\cos(90-l)}_{\text{component of our own velocity along our line of sight.}}$$

V_r: measured radial velocity

Know everything except $V(R)$ and α, which depends on R.

Trick, assume the maximum V_r measured is at the tangent point, where $V_r = V(R)$

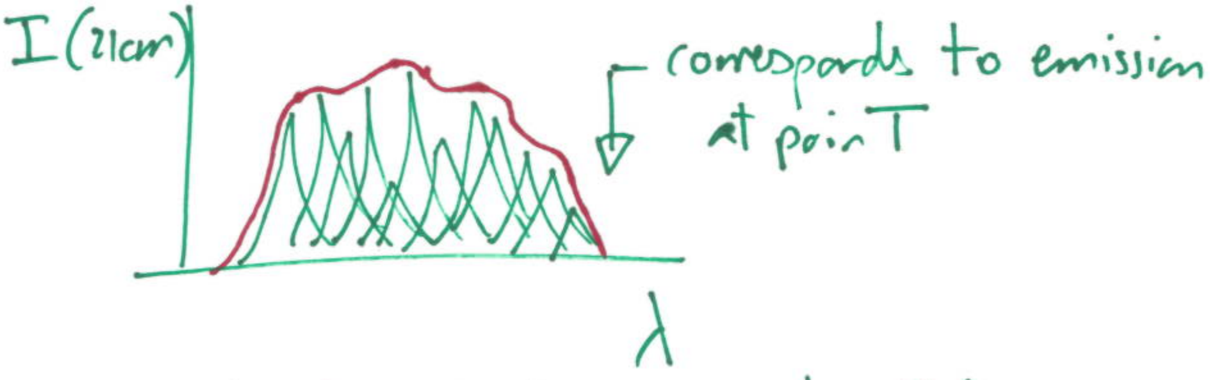
Reasonable assumption, mainly because at that point all of $V(R)$ is along our line of sight (so V_r has a maximum).

$$V_r = V(\underbrace{R}_{R_\odot \sin l}) - V(R_\odot)\cos(90-l)$$

$$\Rightarrow V(R_\odot \sin l) = V_{r,max} + V(R_\odot)\sin l$$

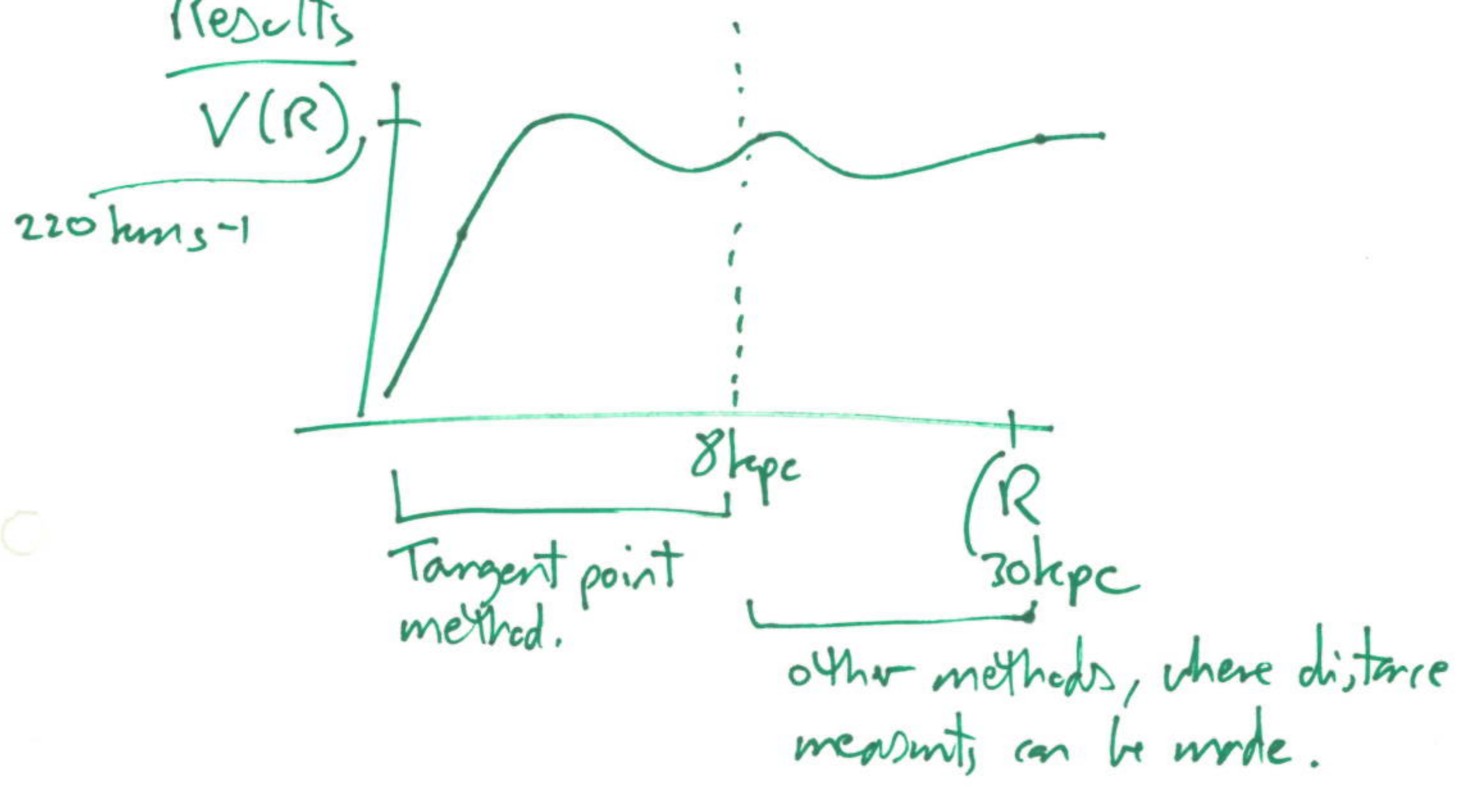
$V_{r,max}$: maximum measured radial velocity.

Example spectrum at one l



By measuring at different l; we get $V(R)$ for different tangent points, and build up the rotation curve of our Galaxy.

Results



$\Rightarrow$ M.W. is also dominated by dark matter!

(recall, density of stars drops off exponentially with a scale length of $\sim$ 2kpc.)

$M_{MW}(< 20\,\mathrm{kpc}) \simeq 2 \times 10^{11} M_\odot$

Using orbits of dwarf galaxies, orbiting the M.W.

$\Rightarrow M_{MW} \gtrsim 10^{12} M_\odot$

$\frac{M}{L} \simeq 5$ within the stellar disc $\left(\frac{M_\odot}{L_\odot}\right)$

$\simeq 50$ to edge of detectable disc.

$\simeq 100$ at orbits of dwarf galaxies.

What is dark matter?

It isn't : normal stars

dust (would be seen by extinction).

gas (" " " " e.g. HI 21cm line, or CO lines).

2 main candidates:

MACHOs : massive compact halo objects.

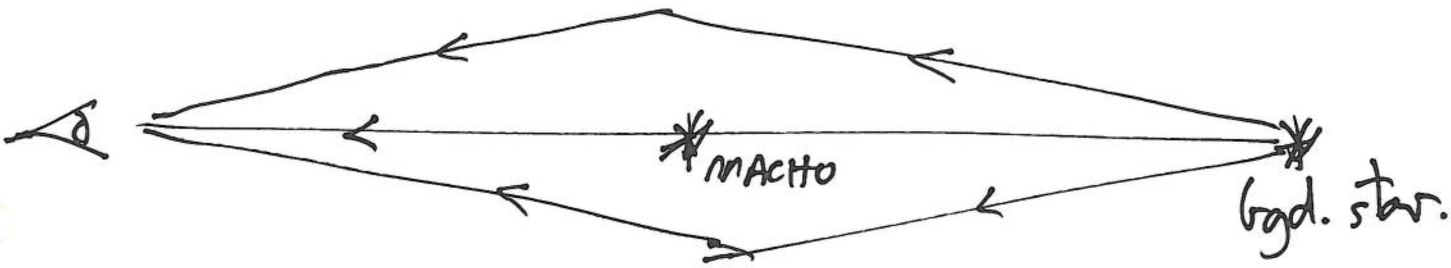
- normal baryonic matter, e.g. planets, brown dwarfs, white dwarf stars, Black holes.

WIMPs : weakly interacting massive particles

14.11.2

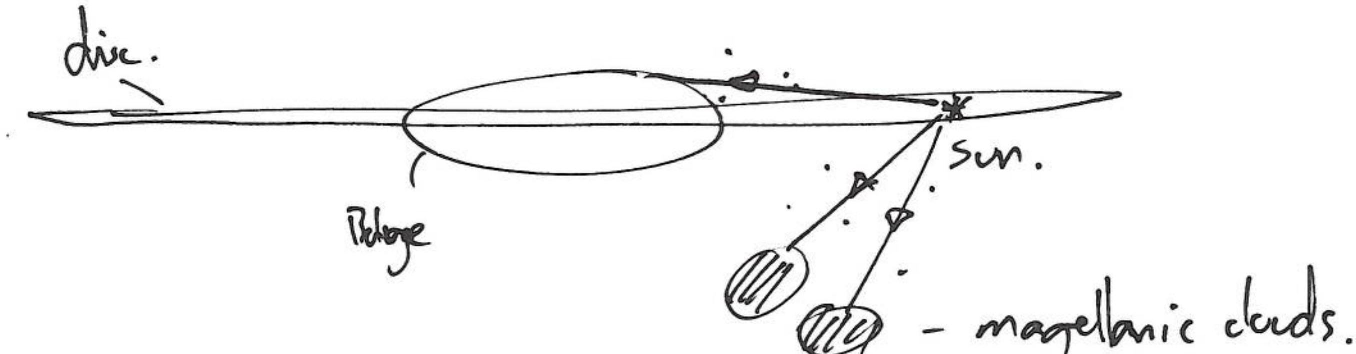
- exotic particle, with mass, but which interacts weakly w normal matter. (e.g. neutrinos).
  └ not neutrinos!

Search for MACHOs via microlensing.



when perfectly aligned, gravitational lensing amplifies the brightness of a bgd. star.
→ G.R. in 4th yr.

microlensing surveys carried out in 1990s, observing in directions with many millions of bgd stars.



Results - 100s of events detected, duration of events sensitive to mass ⇒ $\bar{M} \sim 0.5 M_\odot$
⇒ white dwarf stars.

But, only see enough events to account for $\leq 2\%$ of dark matter in these regions. 14.11.3

Additional evidence from the abundance ratios of elements & isotopes from the big bang (Big Bang Nucleosynthesis) which suggests dark matter cannot be baryonic.

$\longrightarrow$ 3rd yr cosmology.

3rd alternative, that dark matter doesn't exist, and is inferred through relying on incorrect theories of gravity, e.g. modified Newtonian ~~gravity~~ dynamics MOND, $F_g \not\propto \frac{1}{R^2}$

---

3. Distances to galaxies

Need distances in order to measure all main properties:

$\rightarrow$ size, $R \simeq \theta d$
angular size.

$\rightarrow$ luminosity, $L = f \, 4\pi d^2$
flux