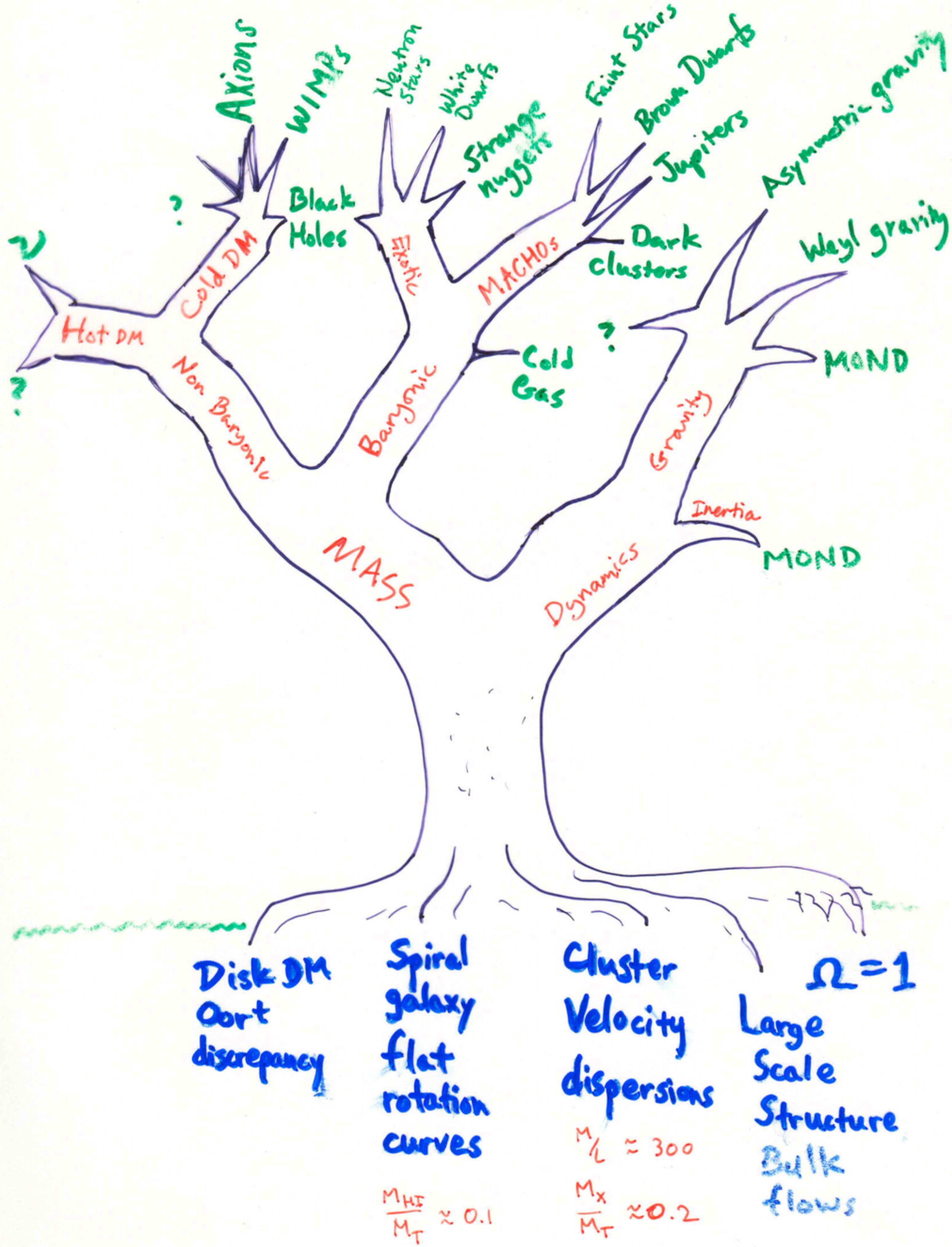
Dark Matter

ASTR 333/433

TODAY

Milky Way Kinematics
Terminal Velocities
Epicycle Approximation

Homework 1
Due next Thursday



Galactic Kinematics

Galactic constants

$$R_0 \ \Theta_0 \ A \ B$$

$$\Omega < \kappa < \nu_z$$

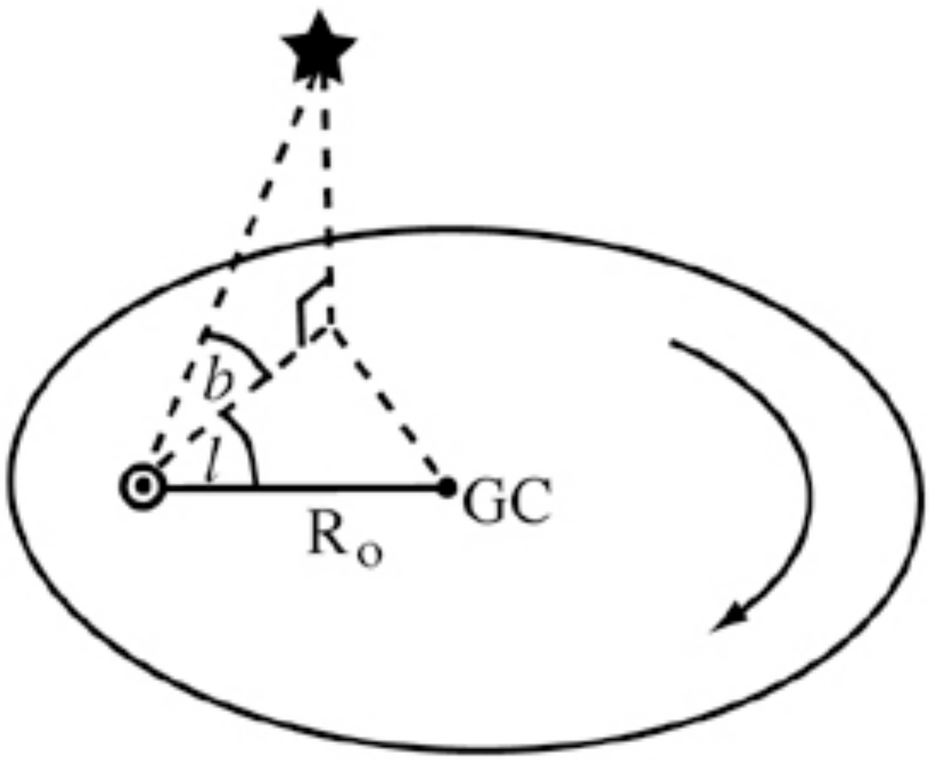
Local Standard of Rest

Epicycle approximation

Galactic Coordinates

from solar system

from Galactic Center



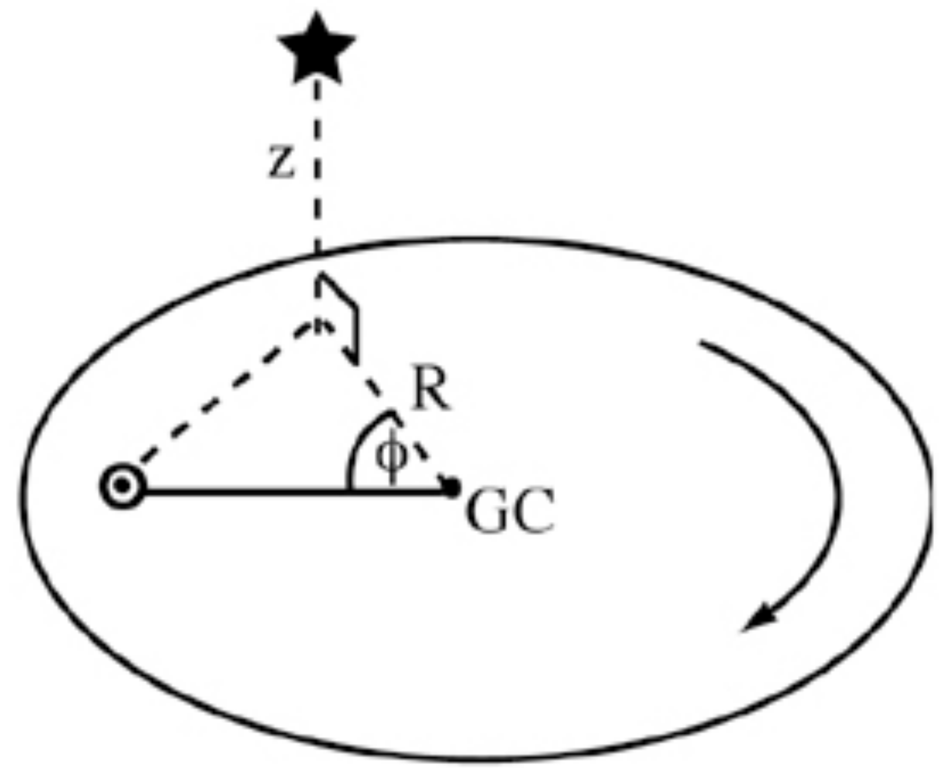


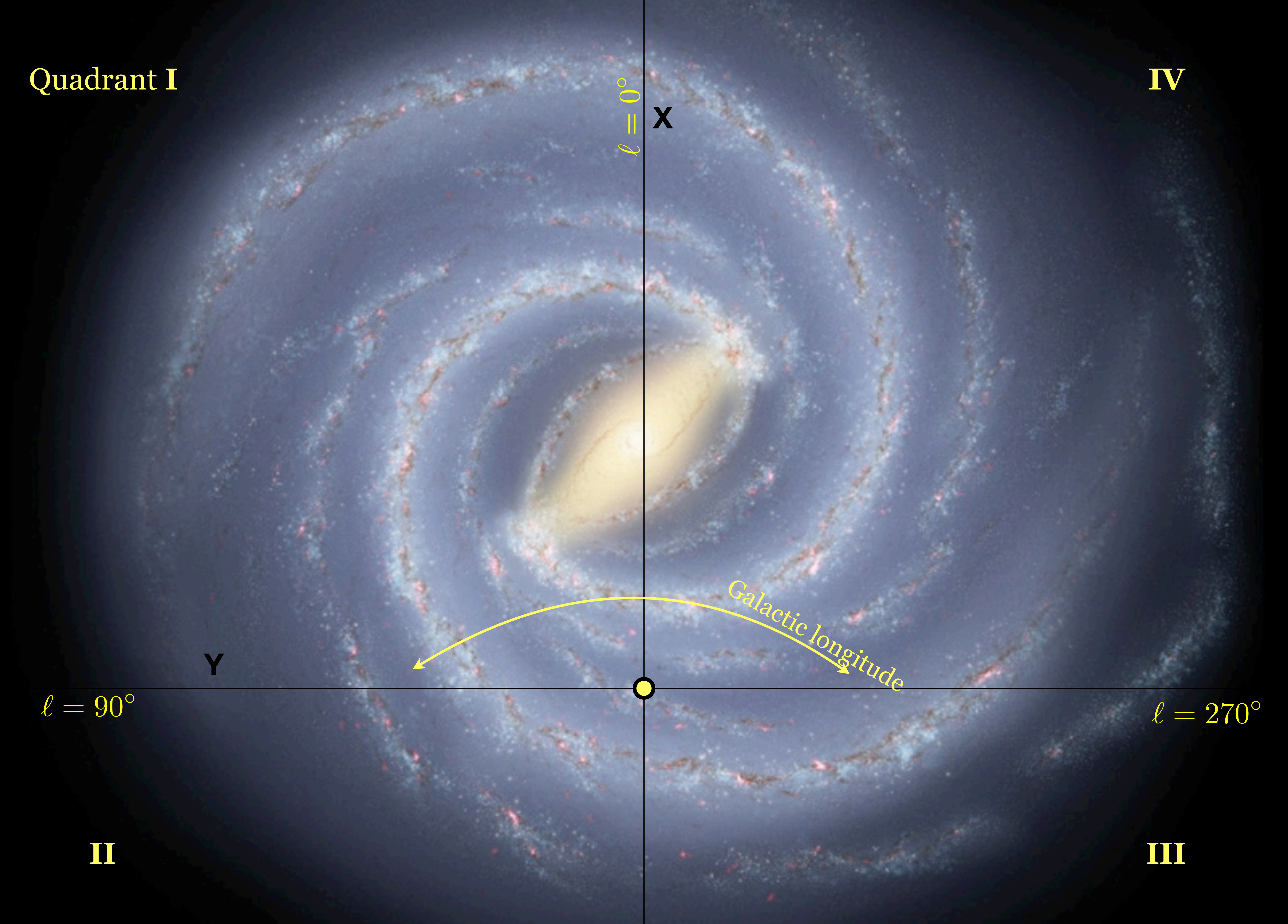
Fig 1.10 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

longitude & latitude

ℓ, b

R, ϕ, z

Galactic mass distribution: bulge/bar, stellar disk, gas disk, dark matter



LSR - local standard of rest

Define a point in space that is moving on a perfectly circular orbit around the center of the galaxy at the Sun's galactocentric distance. We measure all velocities of stars relative to this point, which is known as the **Local Standard of Rest**.

The velocity of the Local Standard of Rest (LSR) is then given by

$$\Pi_{LSR} = 0$$

$$\Theta_{LSR} = \Theta_0$$

$$Z_{LSR} = 0$$

Velocities in these directions are also called U, V, W

More generally, if the Galactic potential is not axis-symmetric (e.g., because of the Galactic bar), then the LSR orbit is oval.

R_0 distance to Galactic Center

Θ_0 orbital velocity of LSR

$$\Omega_0 = \frac{\Theta_0}{R_0}$$ angular velocity of LSR

A Oort constant A

$$A = \frac{1}{2}(\frac{V}{R} - \frac{\partial V}{\partial R})$$

B Oort constant B

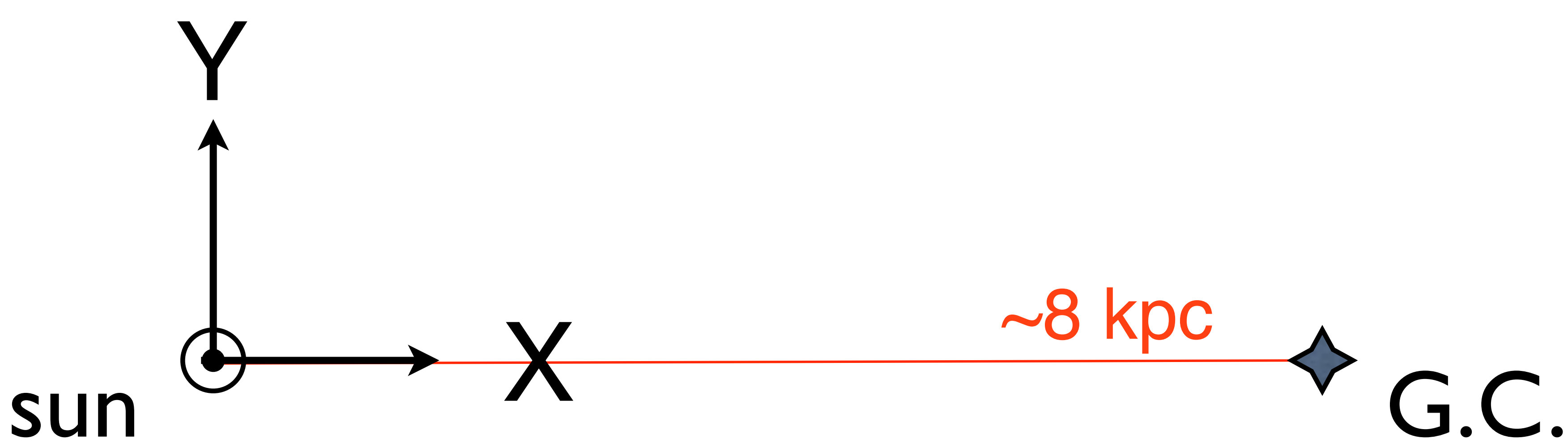
$$B = -\frac{1}{2}(\frac{V}{R} + \frac{\partial V}{\partial R})$$

evaluated at R_0

Local Galactic Coordinates

Cartesian coordinates centered on solar system

As opposed to Galactic Center. Beware sign conventions



X, Y, Z:

X points towards the Galactic Center
Y points in direction of the sun's orbital motion
Z is perpendicular to the Galactic Plane

U, V, W are velocities in these directions

Solar Motion

The residual solar motion wrt the average of local stars is

radial	$U_\odot = 10\,\mathrm{km\,s^{-1}}$	
azimuthal	$V_\odot = 12\,\mathrm{km\,s^{-1}}$	Some say V = 5 km/s, some say 15 km/s!
vertical	$W_\odot = 7\,\mathrm{km\,s^{-1}}$	

The Sun is moving

- a bit towards the galactic center
- faster than the LSR
- northward out of the galactic plane

Currently we are near the mid-plane

(Remember this doesn't account for the rotation of the disk!)

The Velocity Distribution of Stars

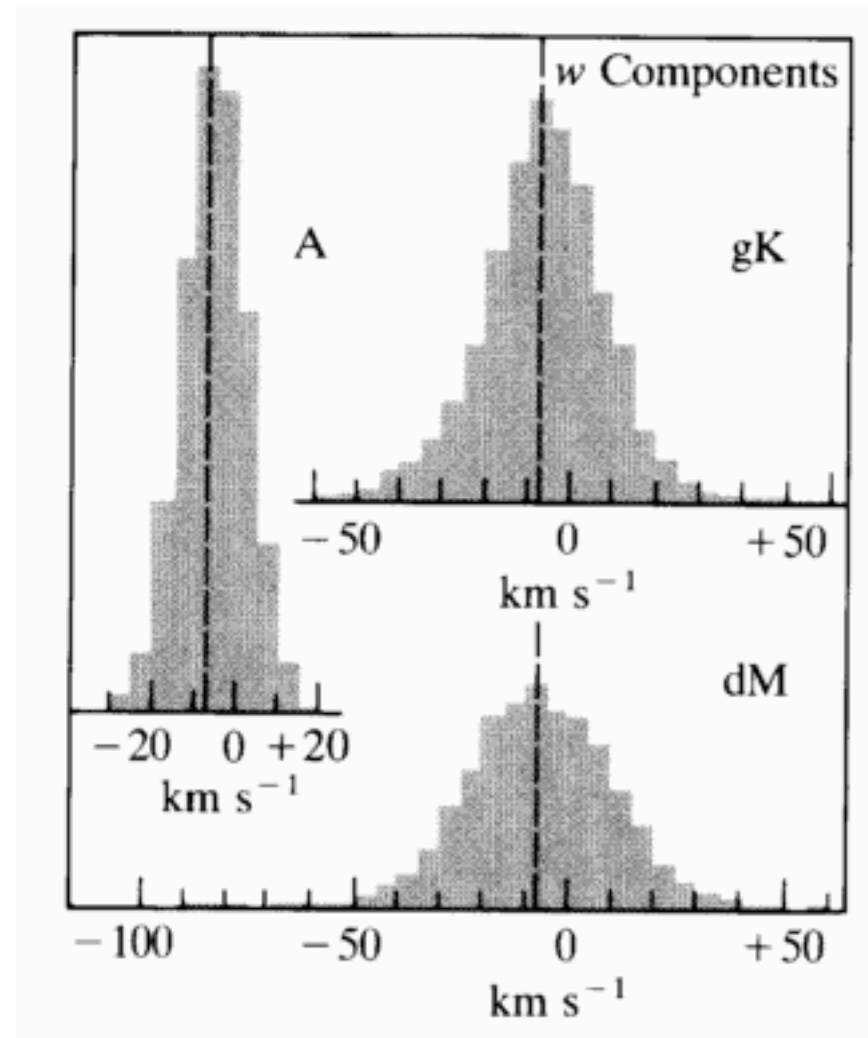
Make a histogram of the Z (up/down) velocities of stars of different spectral type:

- A stars ("A")
- K giants ("gK")
- M dwarfs ("dM")

(what is different about these groups of stars?)

The spread in velocities -- called the **velocity dispersion** and calculated as the standard deviation of the distribution -- is different for each group:

Stars	Dispersion (km/s)
A	9
gK	17
dM	18
white dwarfs	25

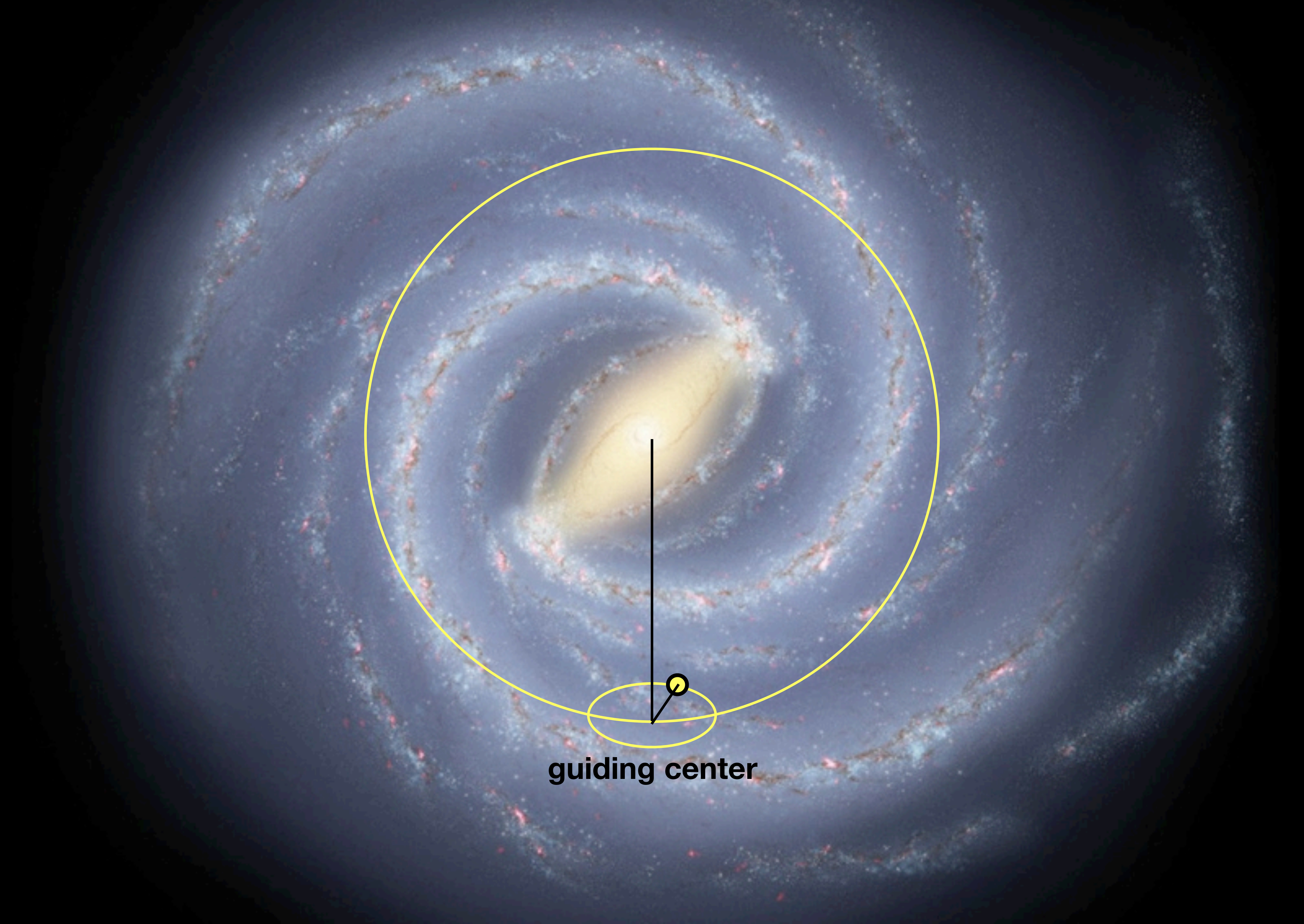


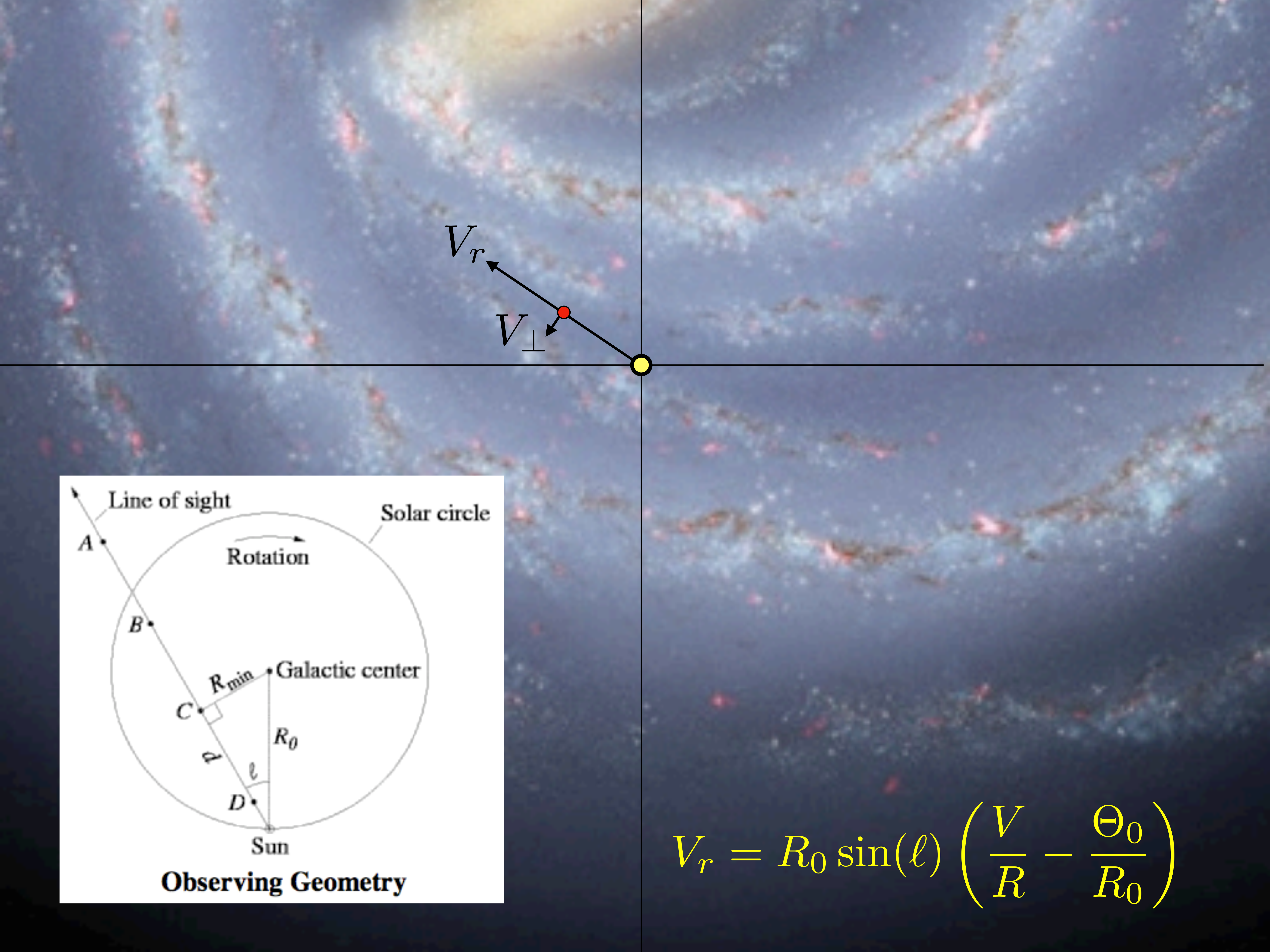
$$\sigma_z = \sqrt{\sum W_i^2}$$

(Oort problem)

$$\sigma_z^2 \approx 2\pi G \Sigma z_0$$

Orbits of individual stars: the epicycle approximation



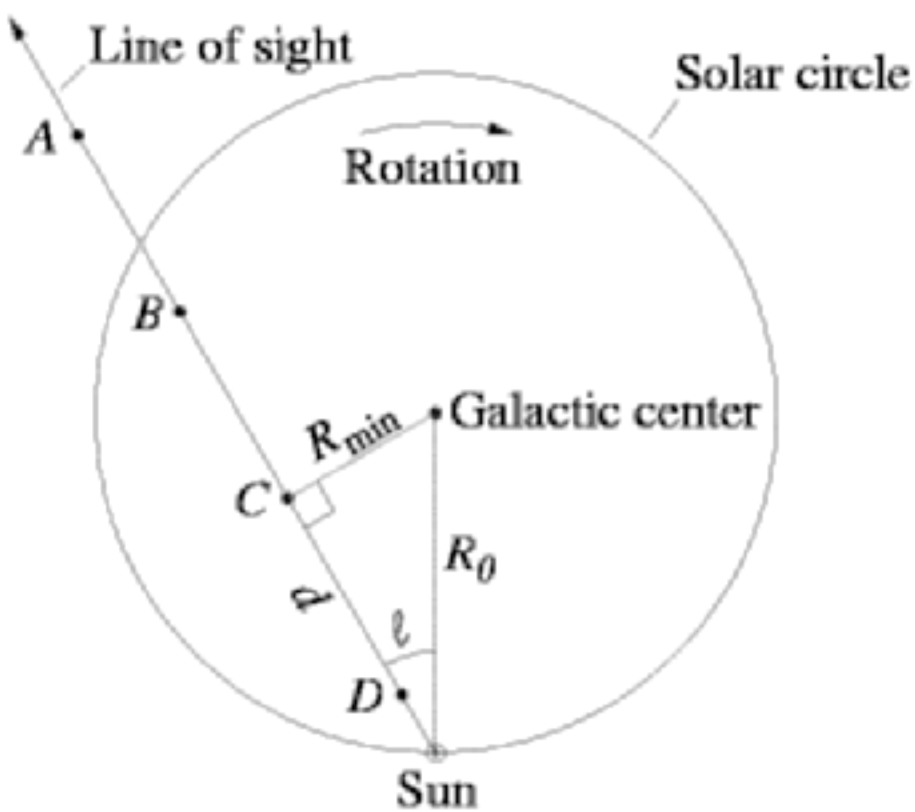


$$V_r = R_0 \sin(\ell) \left(\frac{V}{R} - \frac{\Theta_0}{R_0} \right)$$

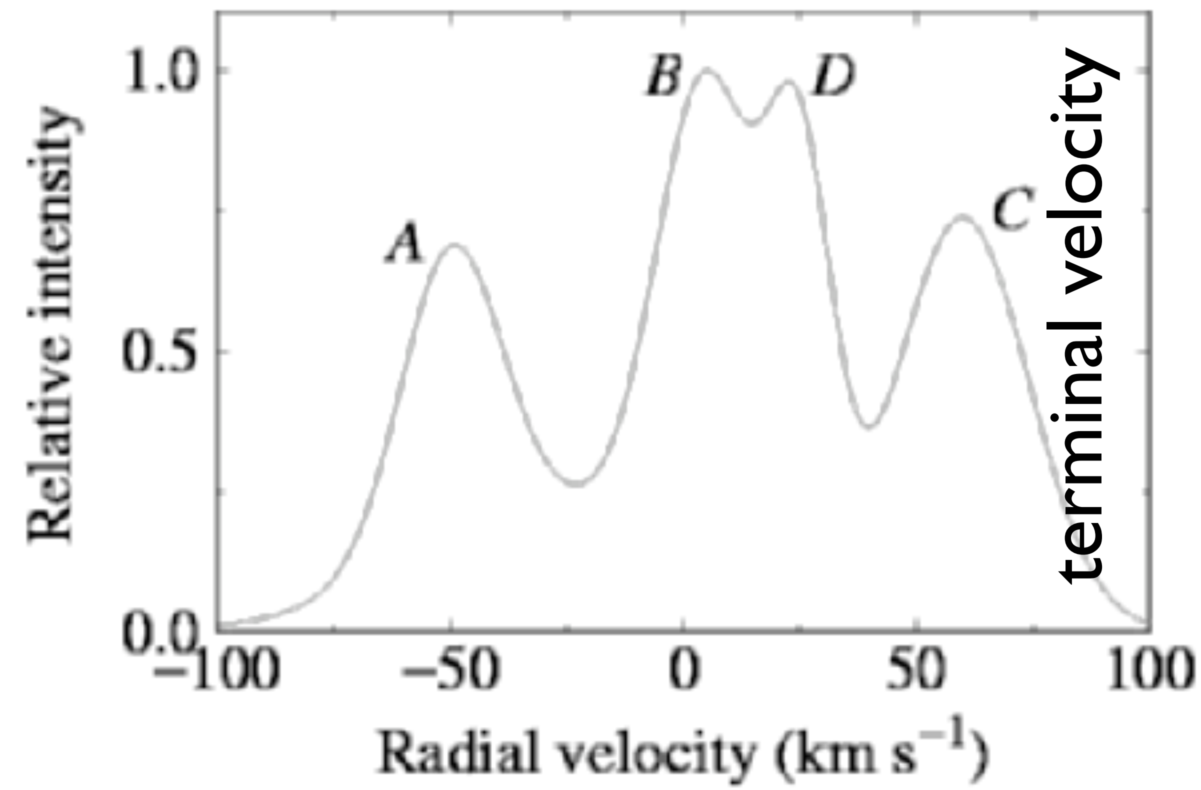
The Tangent-Point Method

Look at gas clouds in the Milky Way. Using 21-cm radio emission, we can get their radial velocity via the doppler shift.

Imagine looking at some line of sight through the galaxy and observing the gas clouds:



Observing Geometry



Observed Velocities

So $v(C) = v(R_{min}) = v(R_0 \sin(l))$.

Maximum velocity at minimum radius along line of sight at Galactic longitude ℓ

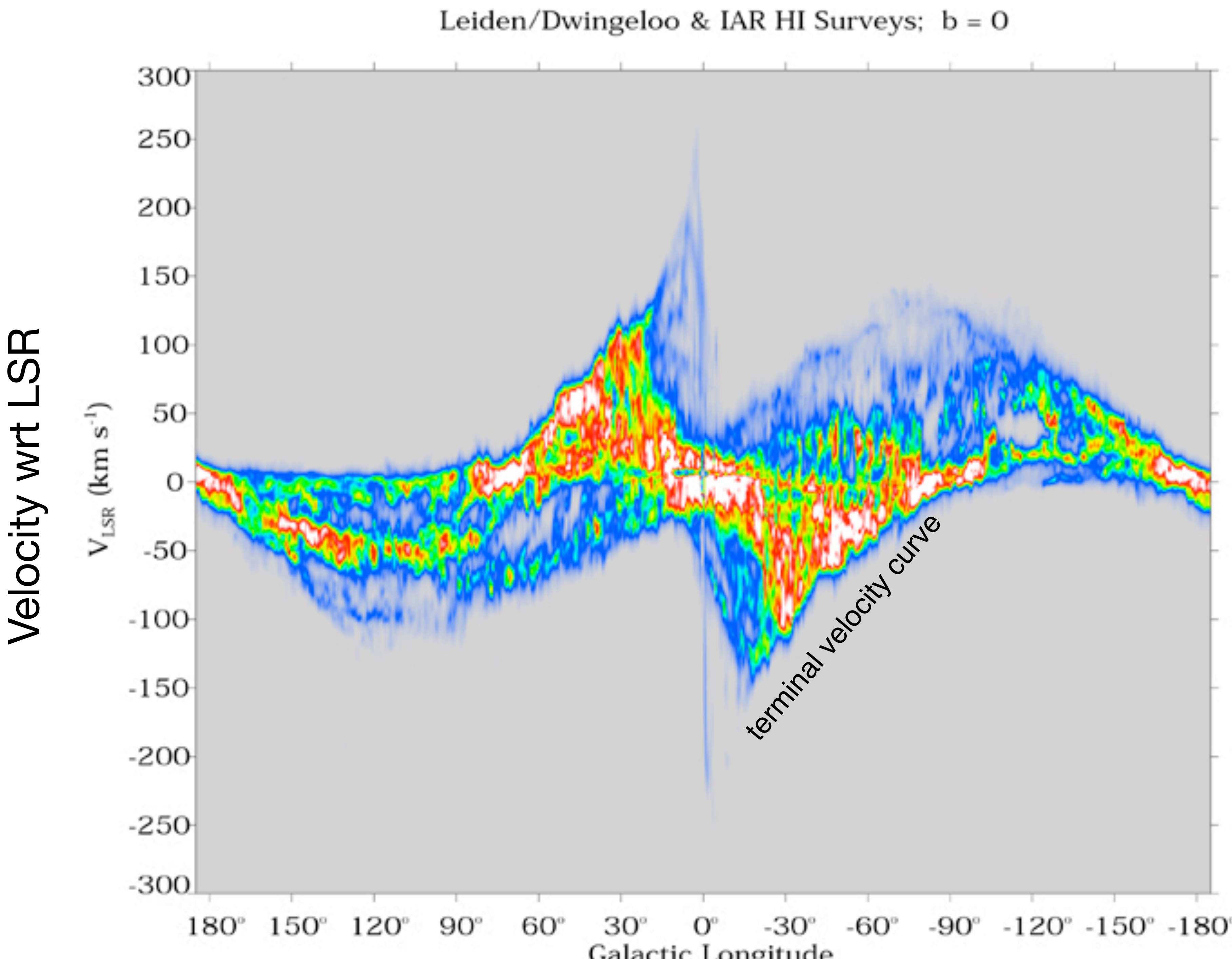
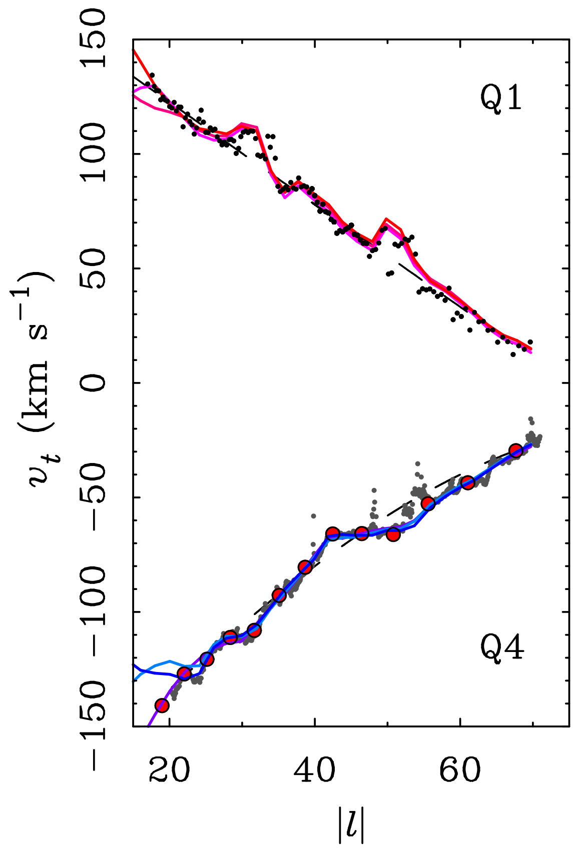


Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

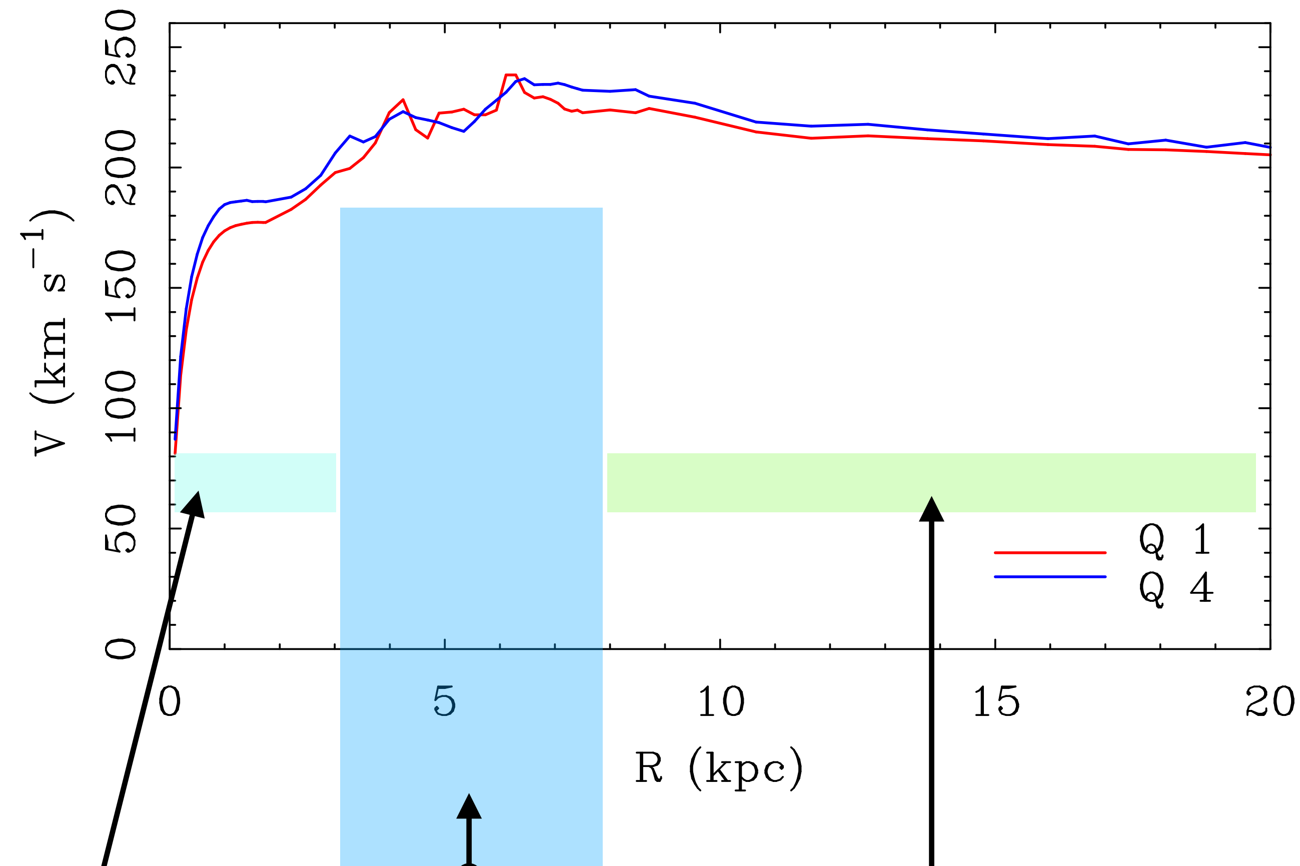
terminal velocities



$$R = R_0 \sin \ell$$

$$V = v_t + \Theta_0 \sin \ell$$

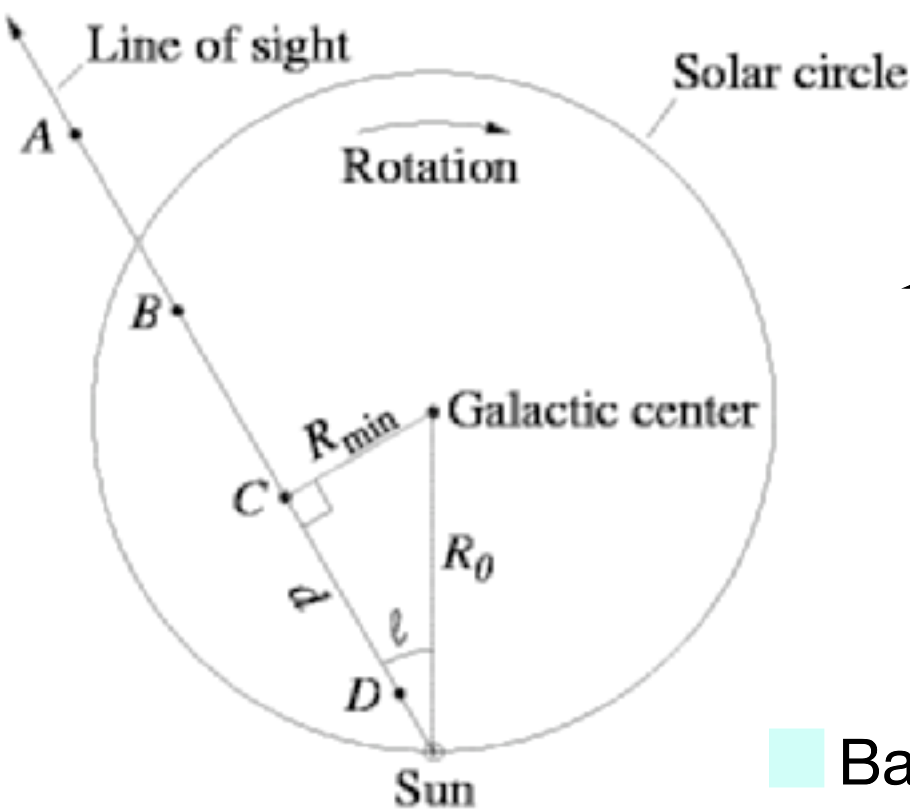
Milky Way rotation curve



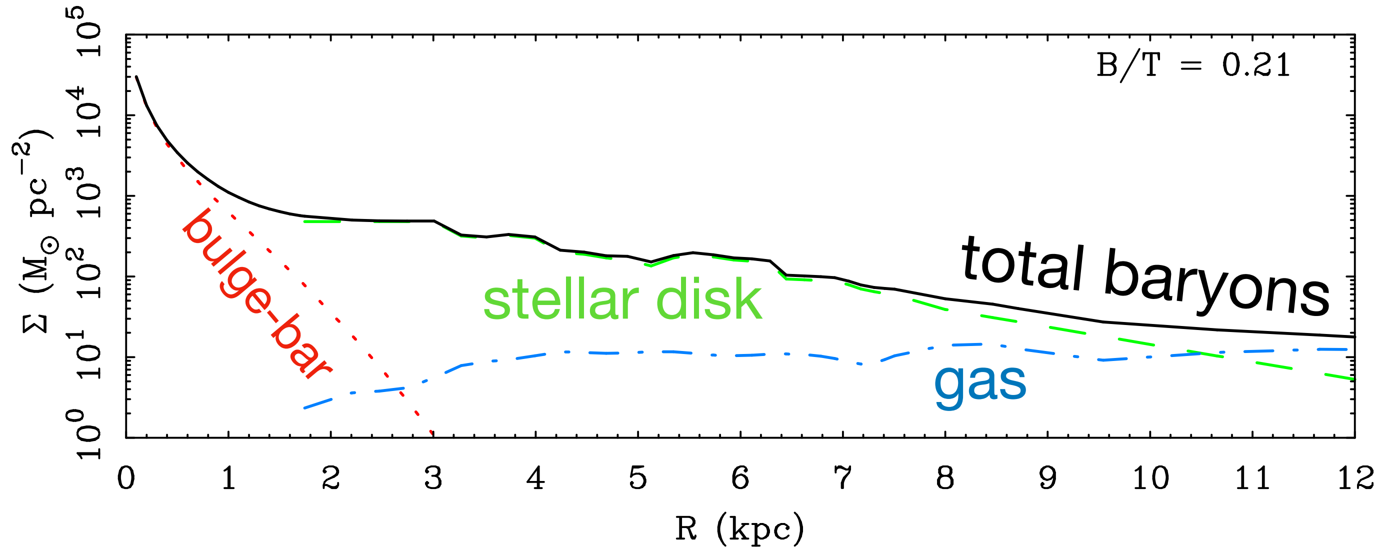
range of measured terminal velocities

model extrapolation

Bar dominates inner radii - assumption of circular motion not valid



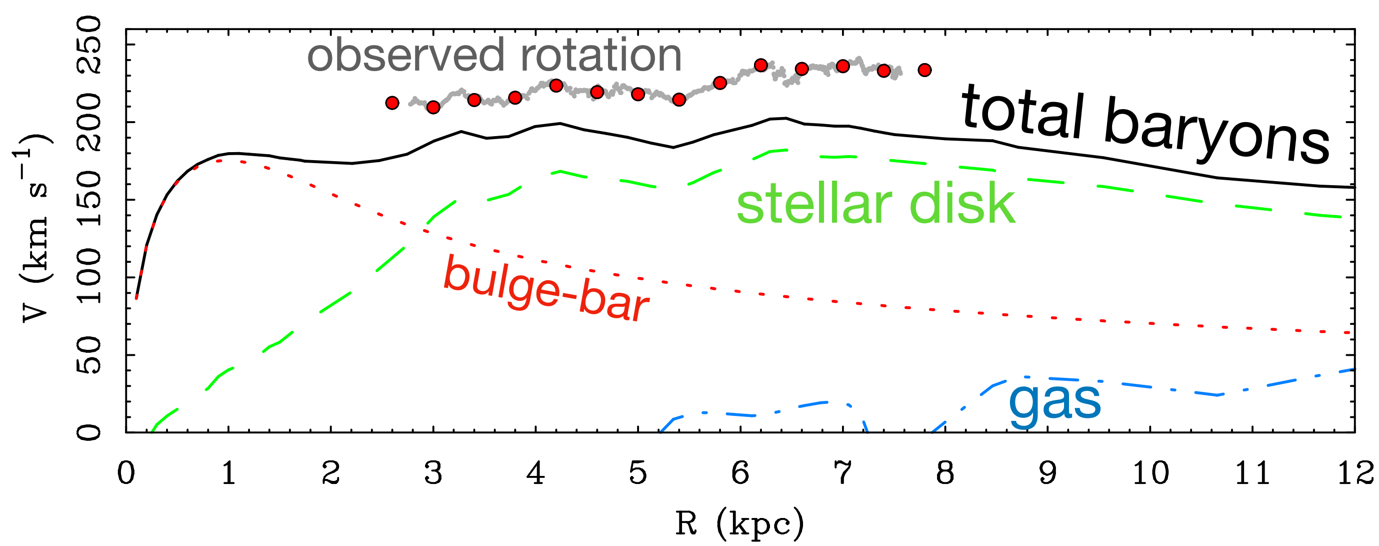
Observing Geometry



Surface density profile

$\Sigma(R)$ *from observed surface brightness profile*

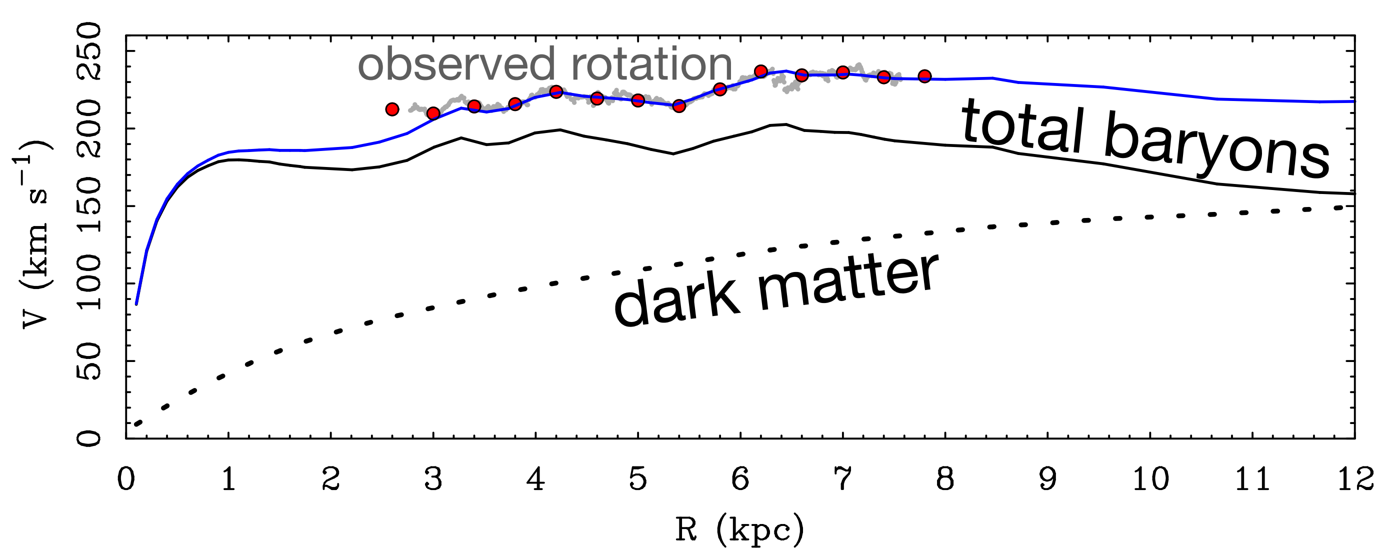
The main uncertainty is the mass-to-light ratio of the stars.



Mass model

$$\frac{V^2}{R} = -\frac{\partial \Phi}{\partial R} = 2\pi G \Sigma(R)$$

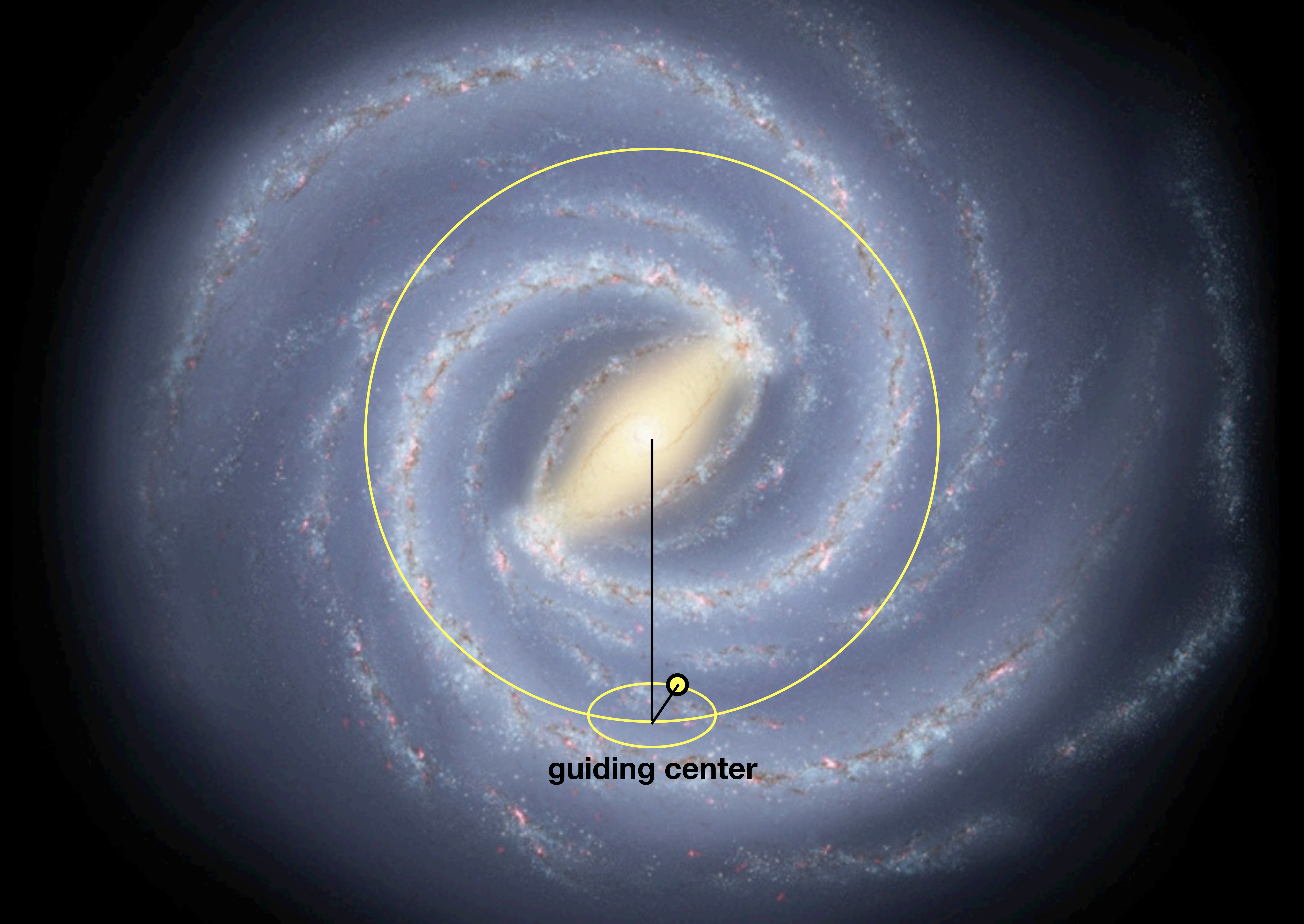
$$V_{DM}^2 = V_{obs}^2 - V_{bar}^2$$



Mass model with DM halo

Total rotation decomposed into baryonic and dark components

Orbits of individual stars: the epicycle approximation



Orbits for 4 individual stars

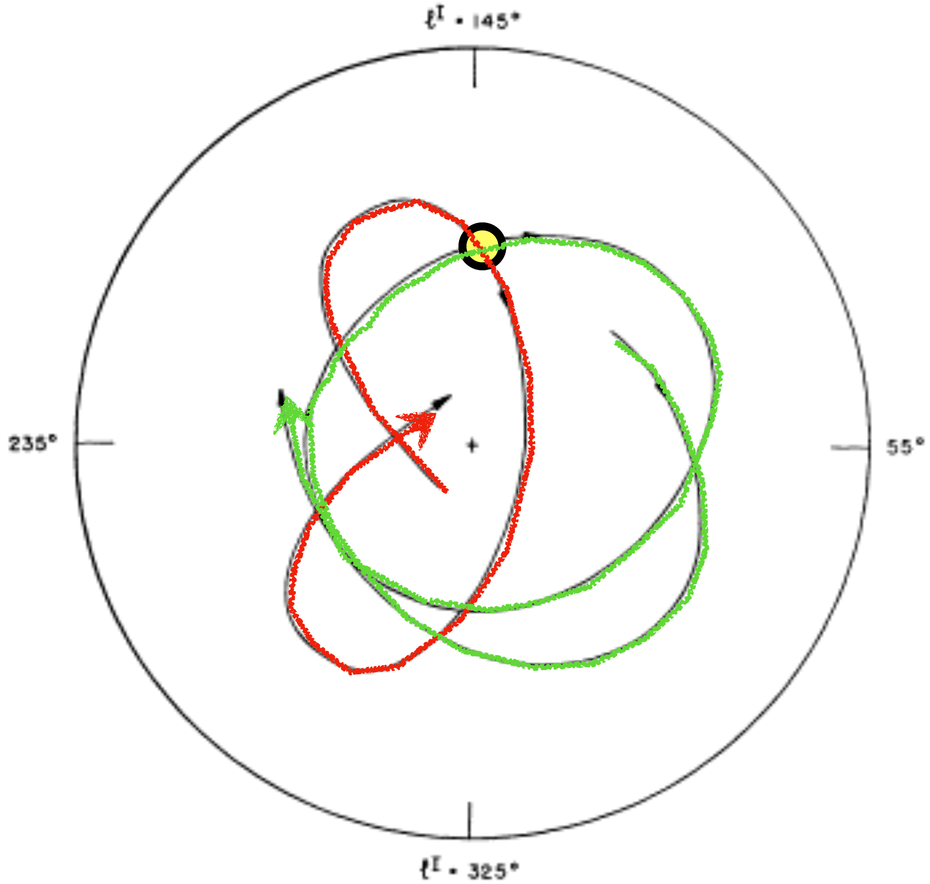


FIG. 2.—Segments of the galactic orbits for two of the program stars. The more circular orbit is for HD 117635 with an ultraviolet excess of $\delta = +0^{m}.05$ The more elliptical orbit is for HD 11980 with $\delta = +0^{m}.17$. Both orbits pass through the solar neighborhood, which is designated by a circle on the $l =$ 145° axis at a distance of 10 kpc from the galactic center The galactic center is shown as a cross The outer circle has a radius of 20 kpc.

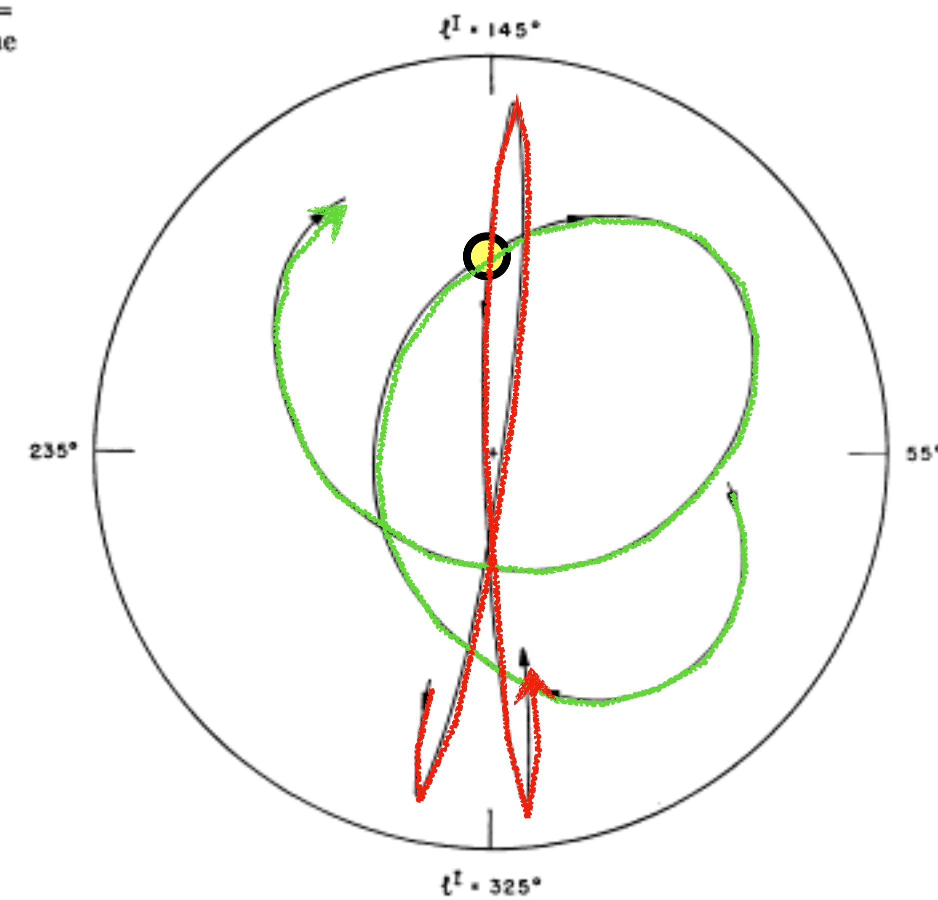
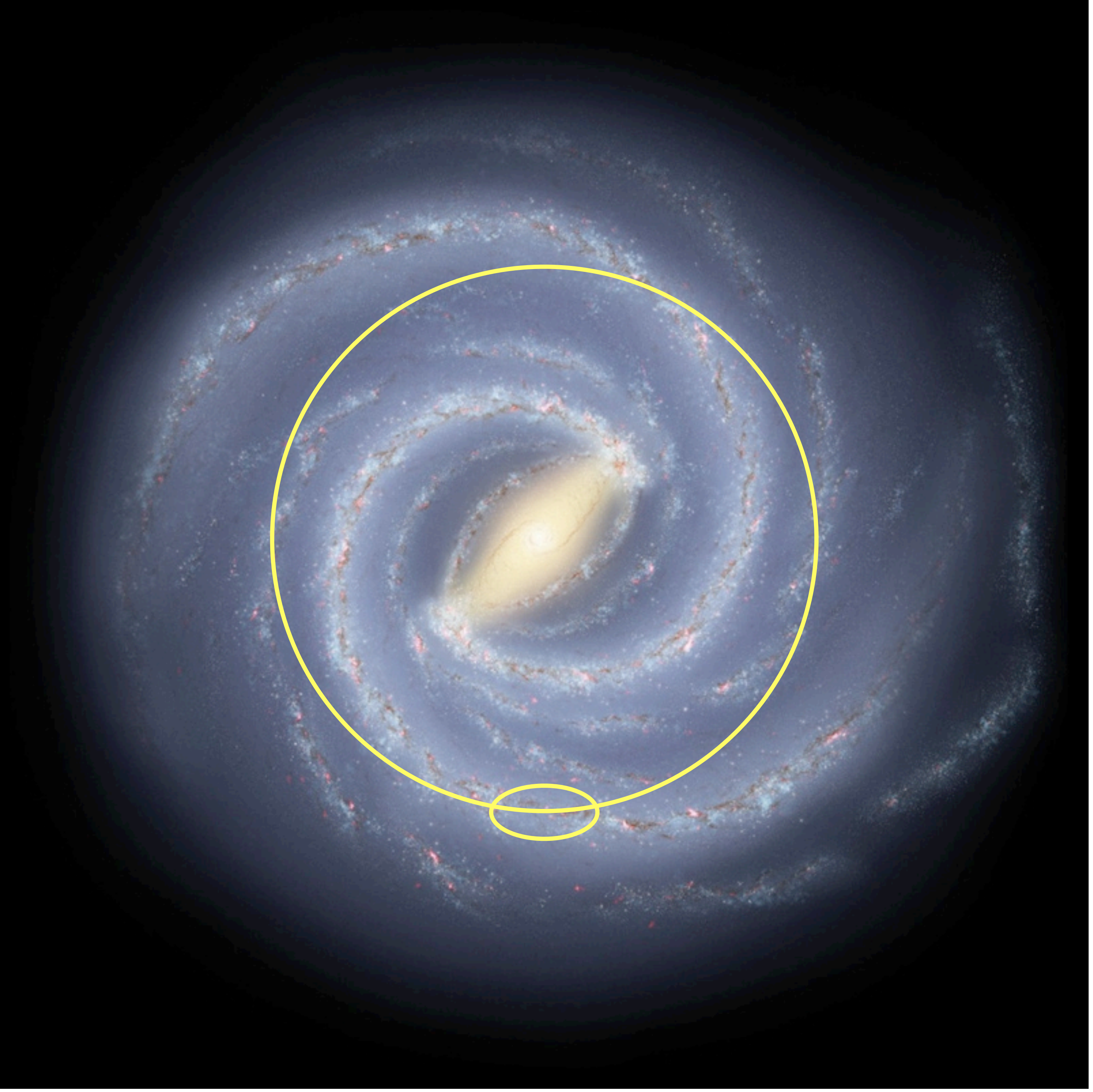
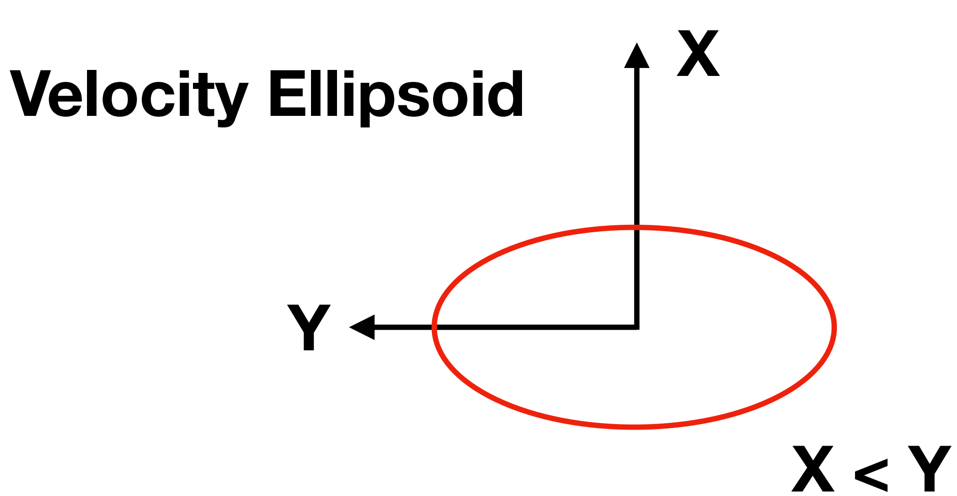


FIG 3.—Same as Fig. 2 The more circular orbit is for HD 29587 with $\delta = +0^{m}.13$. The more elliptical orbit is for Ross 106 with $\delta = +0^{m}.26$. The orbit for Ross 106 is retrograde.

from Eggen, Lynden-Bell, & Sandage (1962)





$$Y = \frac{2\Omega}{\kappa} X$$

$$\frac{\sigma_Y^2}{\sigma_X^2} = \frac{\kappa^2}{4\Omega^2} = \frac{-B}{A-B}$$

in general

$$\sigma_X > \sigma_Y > \sigma_Z$$

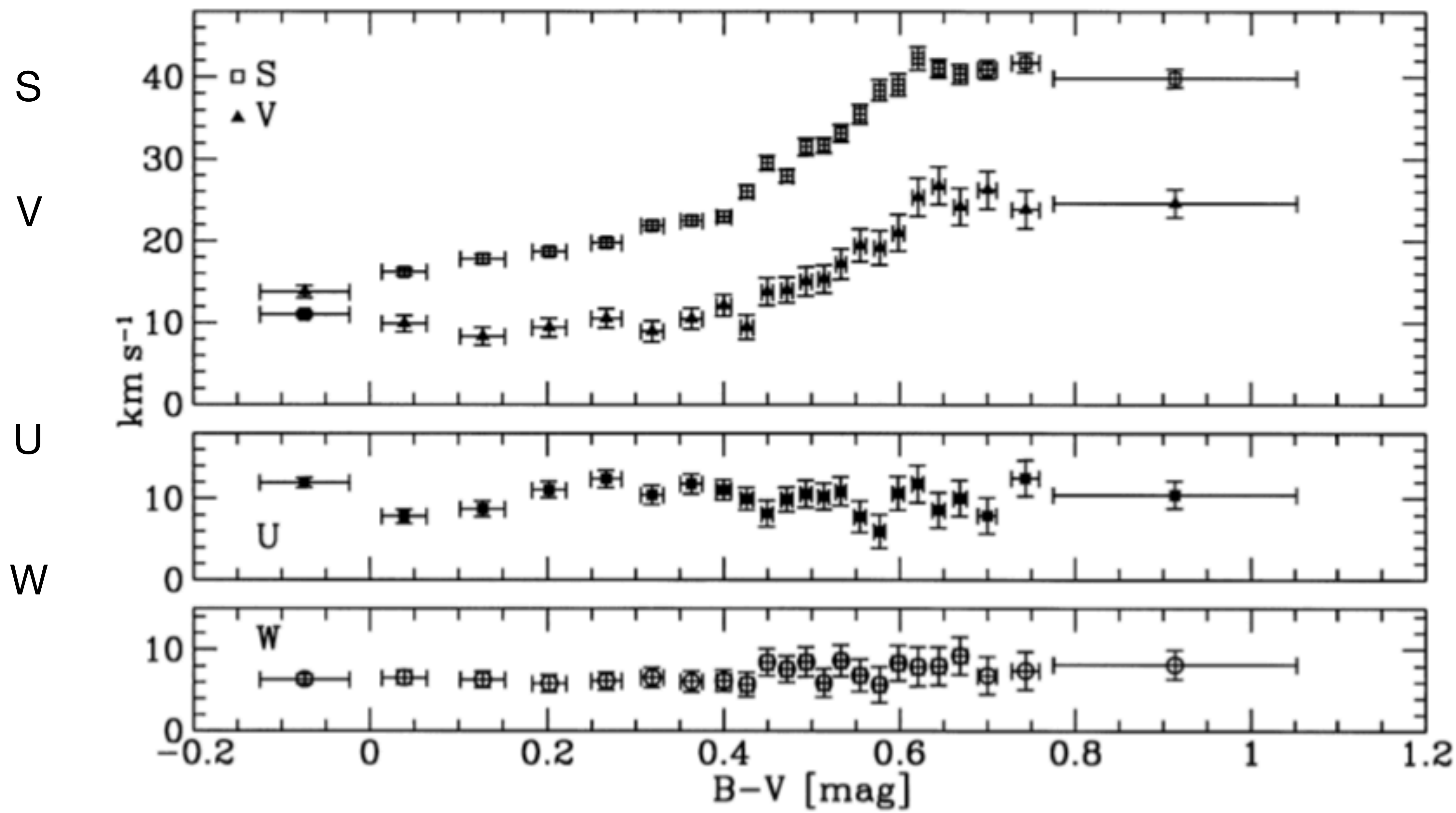
and

$$\Omega < \kappa < \nu_Z$$

which is to say,
the orbital period around the Galaxy is longer than the epicyclic period in radial excursions is longer than the period of vertical oscillations.

The velocity dispersions of stars tends to increases with age.

Circular motion gets deflected into random motion over time.

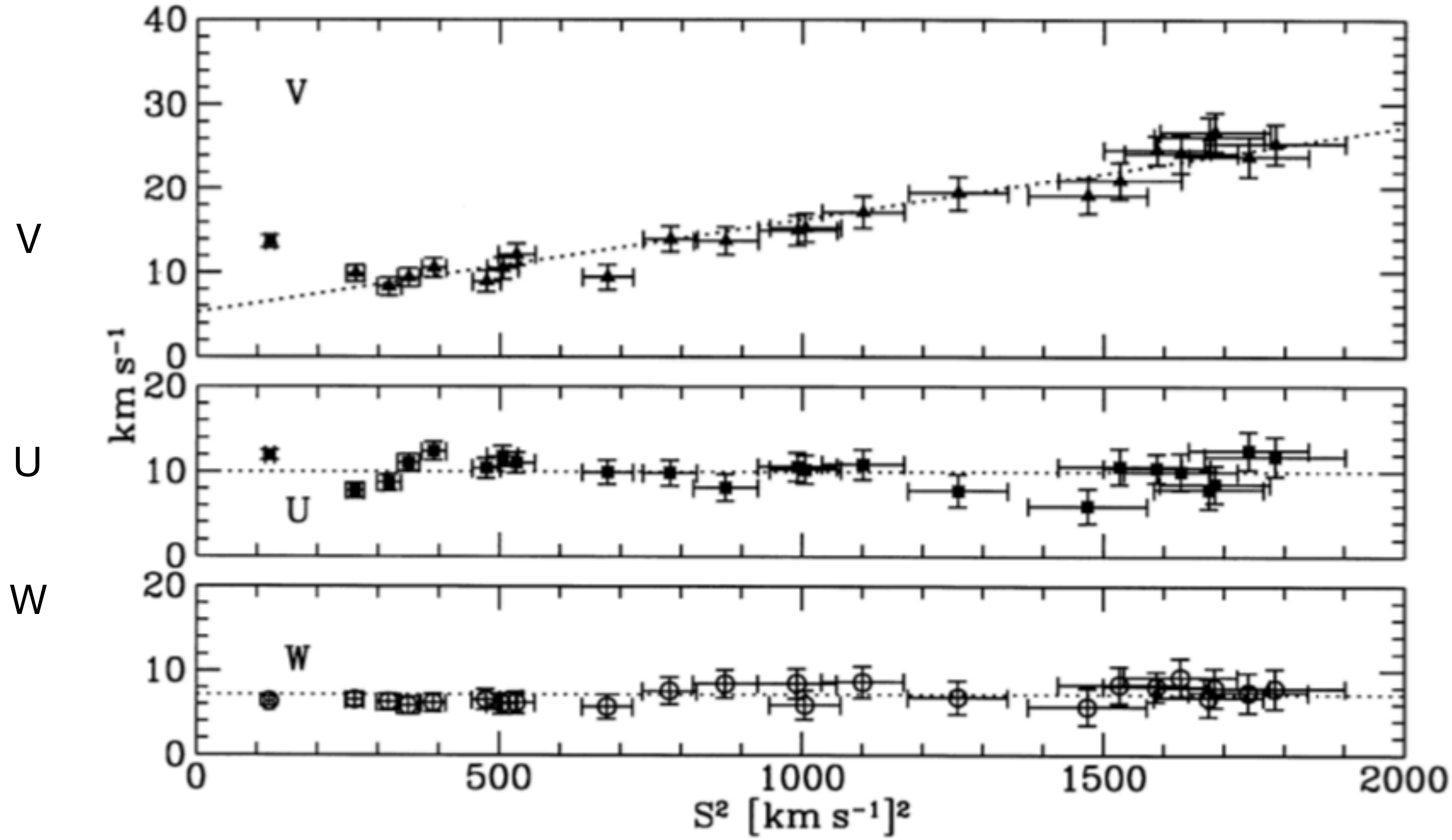


color (age proxy)

he components U, V and W of the solar motion with respect to stars with different colour $B - V$. Also shown is the variation of the dispers

Dehnen & Binney (1998)

Asymmetric drift - stars tend to lag circular speed as dispersion increases.
This is just conservation of energy: circular motion gets deflected into random motion over time.



The dependence of U, V and W on S^2. The dotted lines correspond to the linear relation fitted (V) or the mean values (U and W) for stars
).

Dehnen & Binney (1998)