Ay 20 - Fall 2004 - Lecture 16

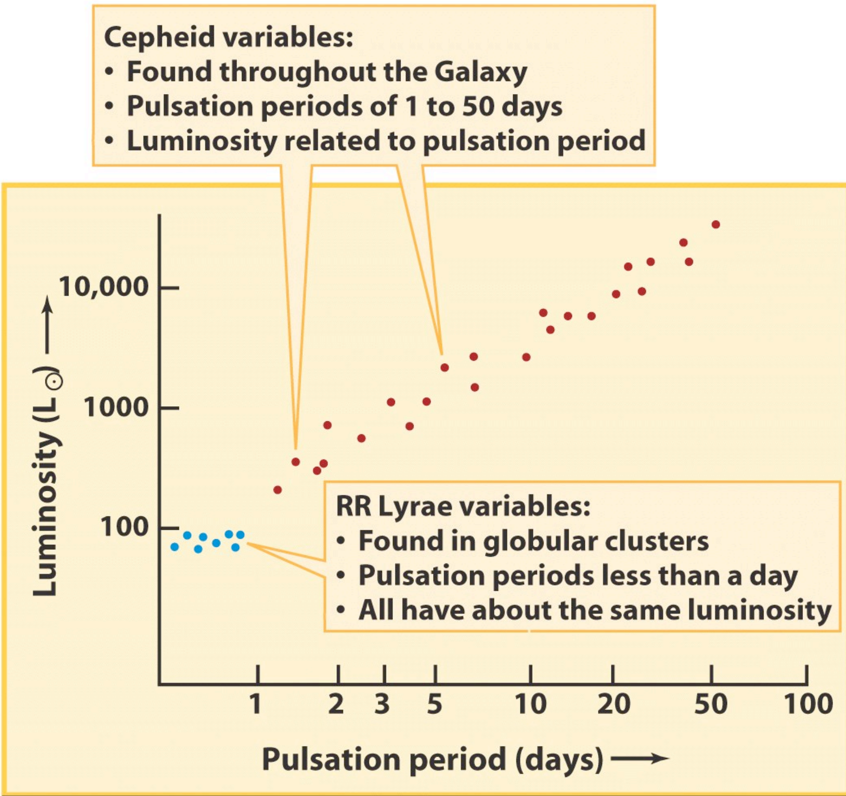
Our Galaxy, The Milky Way

Our Galaxy - The Milky Way

- Overall structure and major components
- The concept of stellar populations
- Stellar kinematics
- Galactic rotation and the evidence for a dark halo
- Galactic center

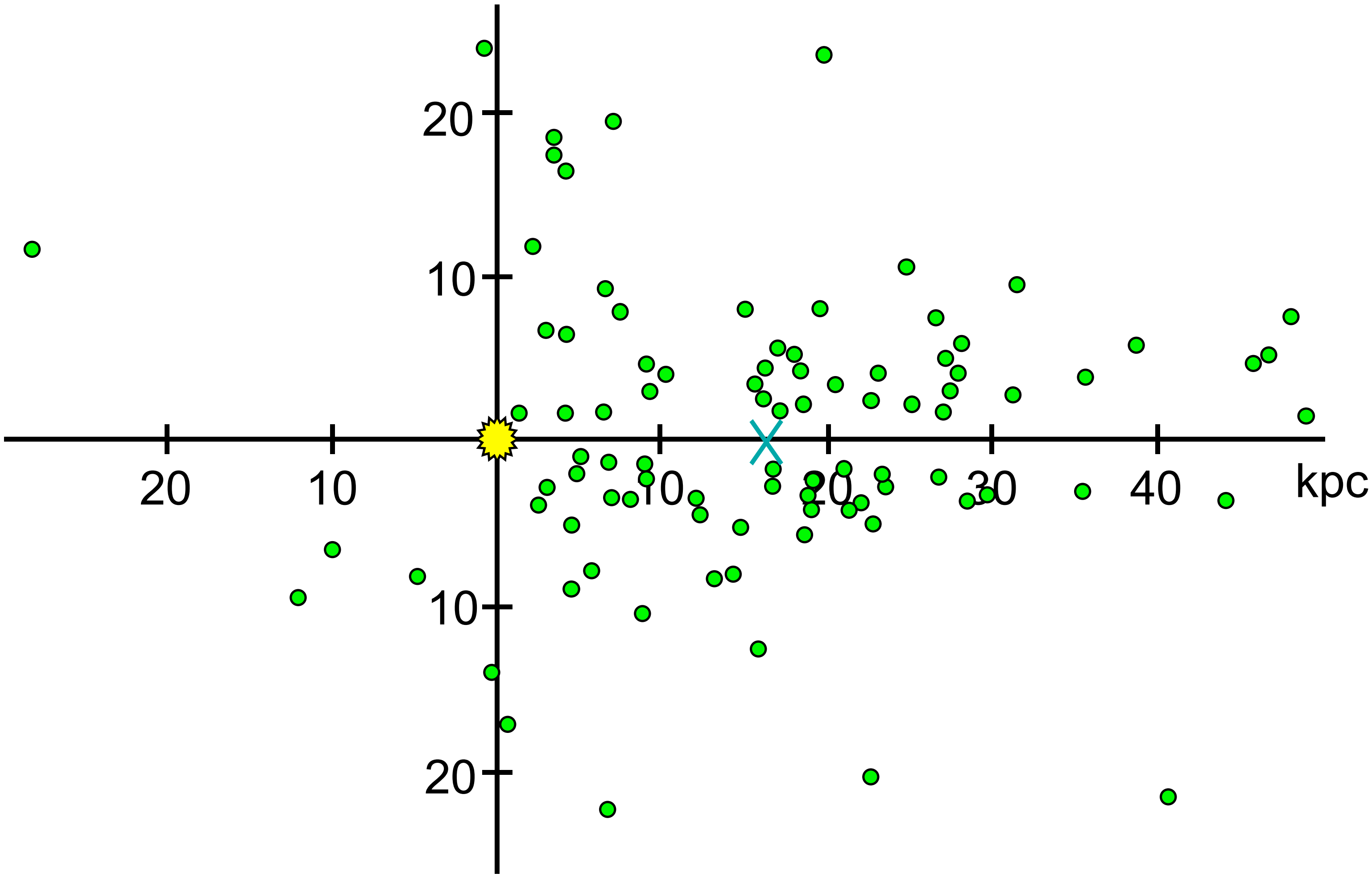
COBE/DIRBE
IR image of our Galaxy

Shapley used RR Lyrae to determine distances to globular clusters, and from there the approximate position of the Sun within the Galaxy.



Our Sun lies within the galactic disk, ~ 8 kpc from the center of the Galaxy

Shapley's Globular Cluster Distribution



A Modern View of the Galaxy

Actually, there is the thin disk, and the thick disk

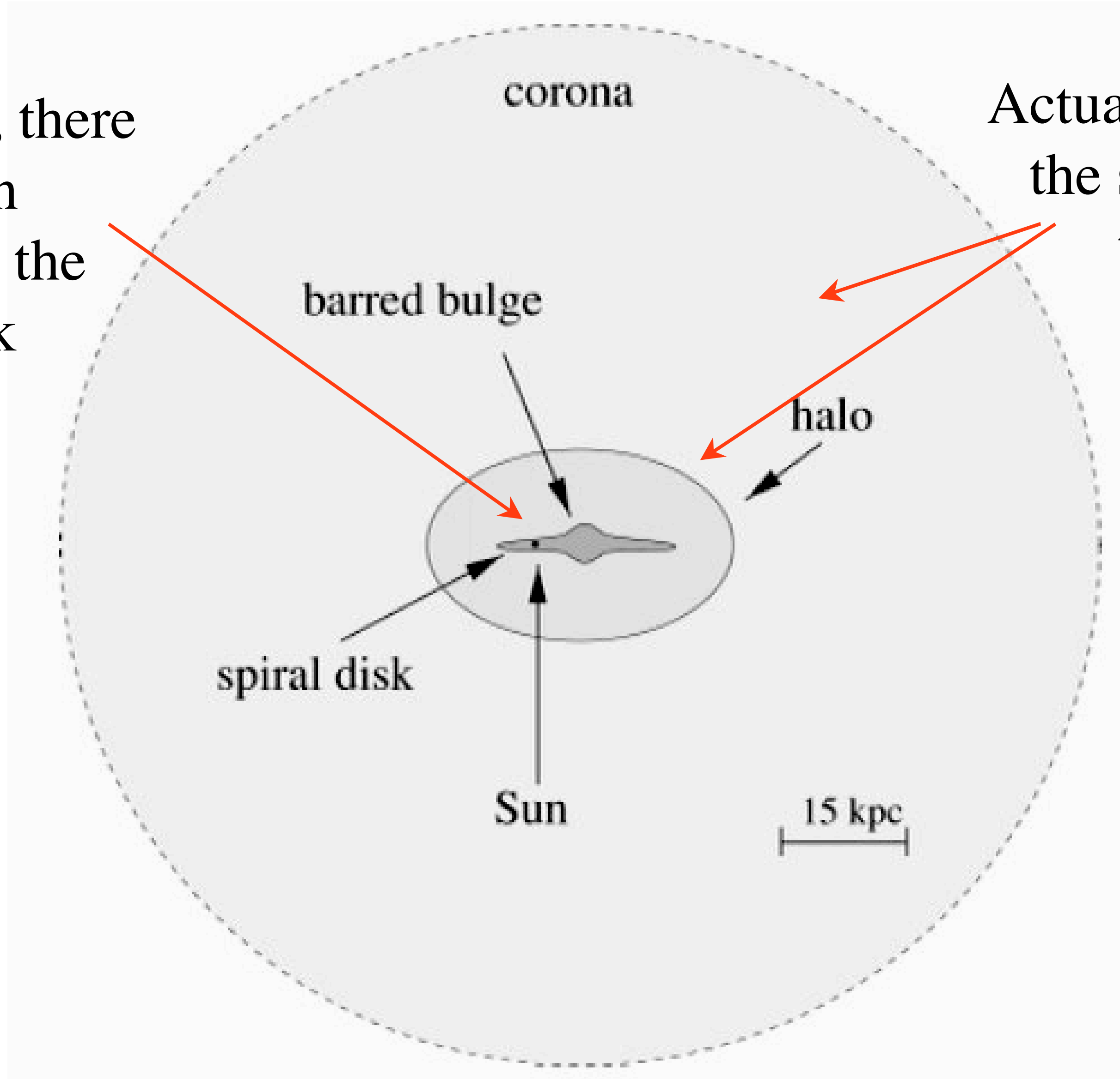


Figure 1. Main structural components of the Milky Way

Actually, there is the stellar halo, the gaseous corona, and the dark halo

Another Schematic View

- There are ~ 2×10^{11} stars in the Galaxy
- An exponential disk ~ 50 kpc in diameter and ~ 0.3 - 1 kpc thick; contains young to intermediate age stars and ISM
- Nested "spheroids" of bulge and halo, containing old stars, hot gas, and dark matter
- The Sun orbits around the center with V ~ 220 km/s, and a period of ~ 2×10^8 yr

Other Spiral Galaxies Indicate How The Milky Way Might Look

NGC 628
Face-On Sc

NGC 891
Edge-On Sb

Major Components of the Galaxy

<u>The disk</u>: thin, roughly circular disk of stars with coherent rotation about the Galactic center.

$$L_{disk} \approx 15 - 20 \times 10^9 L_{sun}$$

$$M_{disk} \approx 6 \times 10^{10} M_{sun}$$

Disk extends to at least 15 kpc from the Galactic center. Density of stars in the disk falls off exponentially, both radially and vertically:

$$n(R) \propto e^{-R/h_R}$$

disk scale length $h_R \sim 3$ kpc

Most of the stars (95%) lie in a **thin disk,** with a vertical scale height ~ 300 pc. Rest form a **thick disk** with a vertical scale height ~ 1 kpc. Thin disk stars are younger.

Also a gas disk, thinner than either of the stellar disks.

Major Components of the Galaxy

- **<u>The bulge</u>**: central, mostly old spheroidal stellar component:

$$L_{bulge} \approx 5 \times 10^{9} L_{sun}$$

$$M_{bulge} \approx 2 \times 10^{10} M_{sun}$$

Galactic center is about 8 kpc from the Sun, the bulge is a few kpc in radius

- **<u>The halo</u>**, contains:

(i) Field stars - total mass in visible stars ~10^9 M_{sun}. All are old, metal-poor, have random motions. Very low density.

(ii) Globular clusters. A few % of the total halo stellar content.

(iii) Gas with T ~ 10^5 - 10^6 K. Total mass unknown.

(iii) Dark matter. Physical nature unknown. About 90% of the total mass.

Principal Components of the Galaxy

Table 1. Some population characteristics of disk and halo components in the solar neighborhood.

Component	Scale height (pc)	$\langle[Fe/H]\rangle$	$\sigma_U, \sigma_V, \sigma_W$ [a] (km s^{-1})	V_{lag} [a] (km s^{-1})	Age (Gyr)	ρ/ρ_{tot} [b]
Old thin disk	300	−0.3	30, 20, 15	15	≤10	0.95–0.98
Thick disk	800–1500	−0.6	65, 55, 40	40	12–15	0.02–0.05
Metal-weak thick disk	1400:	−1.2:	Unknown	40	(12–15):	(0.0005–0.002):
Flattened halo (also called old, low or collapsed halo)	1600–2000	−1.6: [c]	130:, 100:, 90: [c]	160	12:–15	0.0008:
Spherical halo (also called younger, high or accreted halo)	Spherical	−1.6: [c]	130:, 100:, 90: [c]	270	12:	0.0002:

[a] σ_U, σ_V and σ_W are velocity dispersions in the directions away from the Galactic center, toward Galactic rotation and toward the north Galactic pole, respectively. V_{lag} ($=V_{solar\ nbd.} - V$) measures the asymmetric drift, the velocity by which the component lags the solar neighborhood in its systemic rotation.

[b] Ratio of the density of the component to total density in the solar neighborhood. We assume $\rho_{halo}/\rho_{disk} = 0.001$.

[c] Decomposition of the two halo components has not yet been achieved. The tabulated values are those determined for their admixture in the solar neighborhood. The values of the individual components are thus uncertain.

The Concept of Stellar Populations

- Originally discovered by Baade, who came up with 2 populations:

  Pop. I: young stars in the (thin) disk, open clusters

  Pop. II: old stars in the bulge, halo, and globular clusters

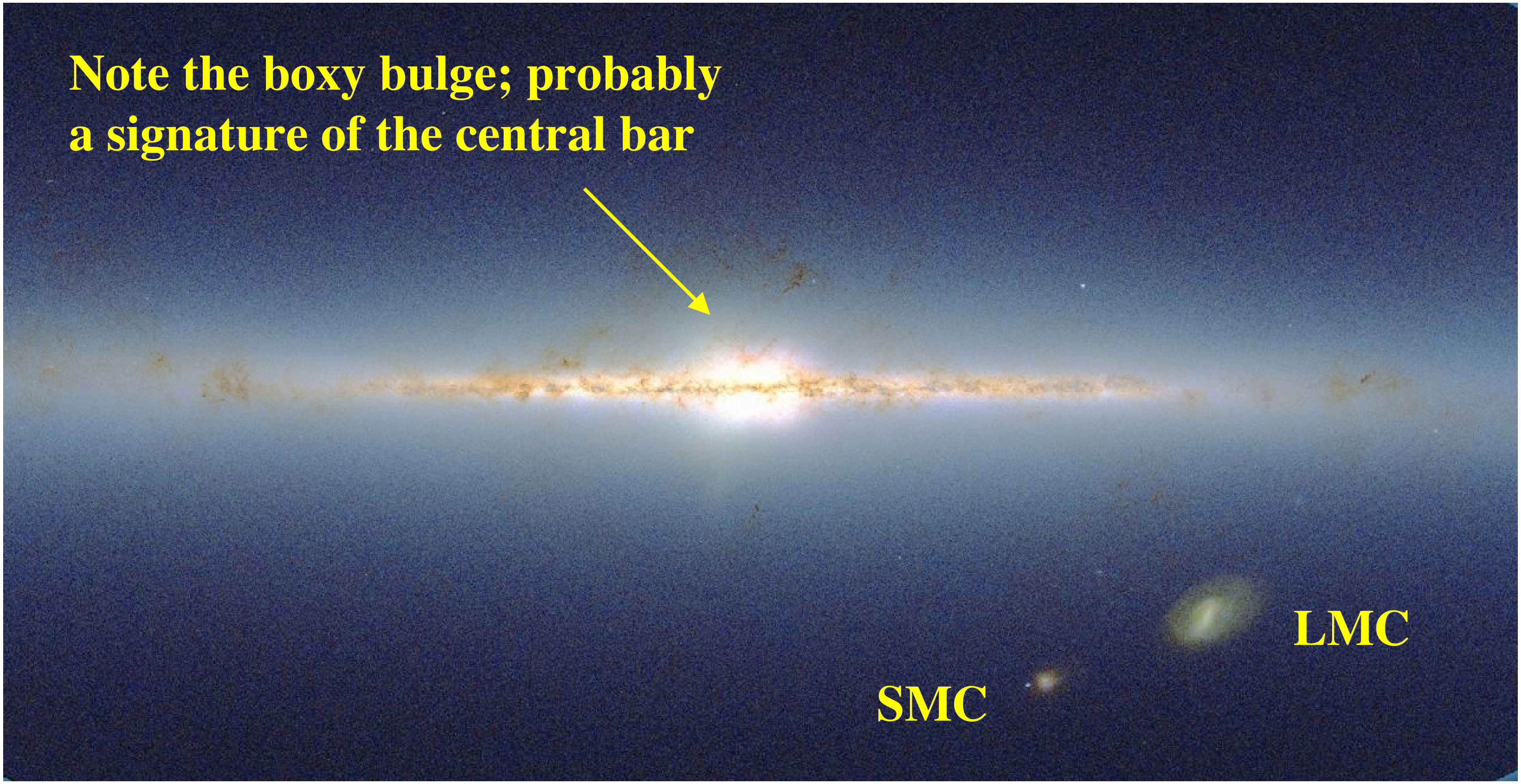
  - Today, we distinguish between the old, metal-rich stars in the bulge, and old, metal-poor stars in the halo
  - Not clear whether the Pop. I is homogeneous: young thin disk, vs. intermediate-age thick disk
- A good modern definition of stellar populations:

  Stellar sub-systems within the Galaxy, distinguished by density distributions, kinematics, chemical abundances, and presumably formation histories. Could be co-spatial.

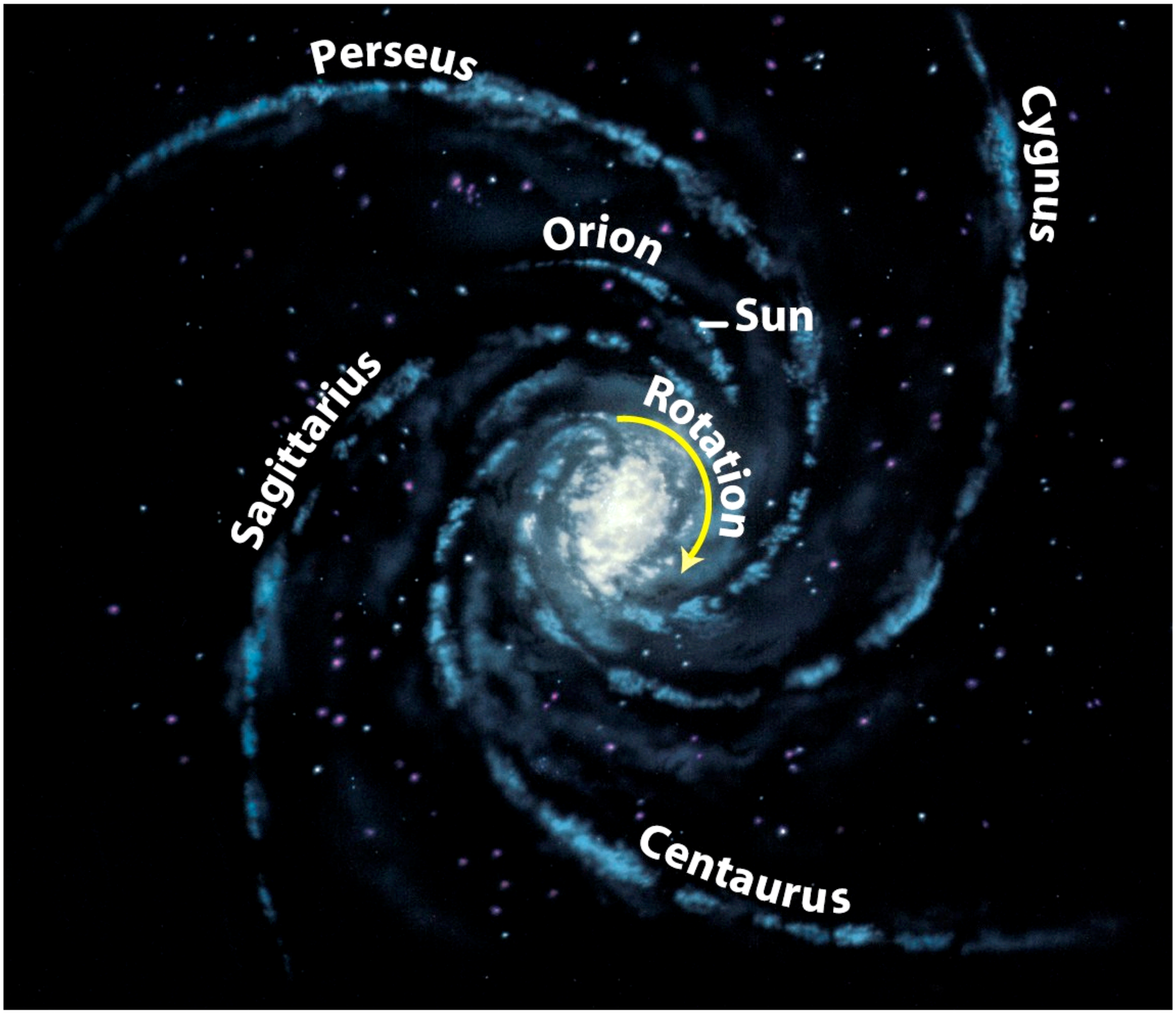
Due to the dust obscuration, the best ways to probe the Galactic structure are in infrared, and H I 21 cm line, which also provides the kinematics.

An IR View of the Galaxy:

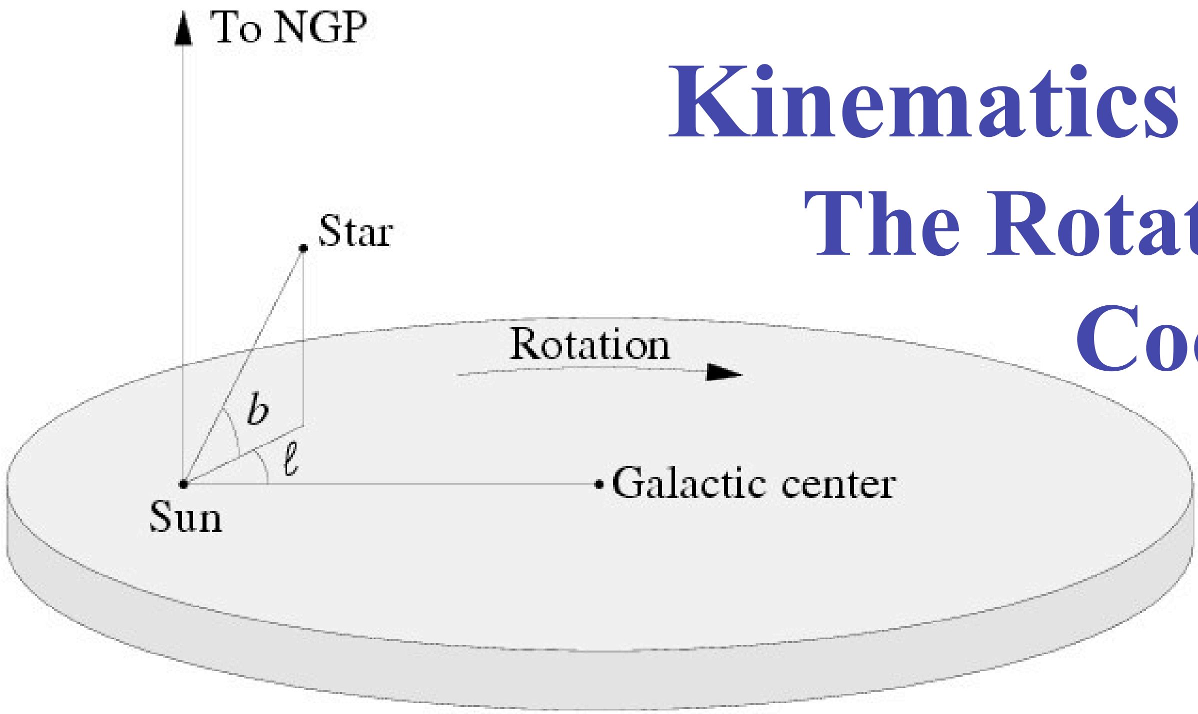
(2MASS JHK composite, clipped a bit in longitude)



OB associations, H II regions, and molecular clouds in the galactic disk outline the spiral arms



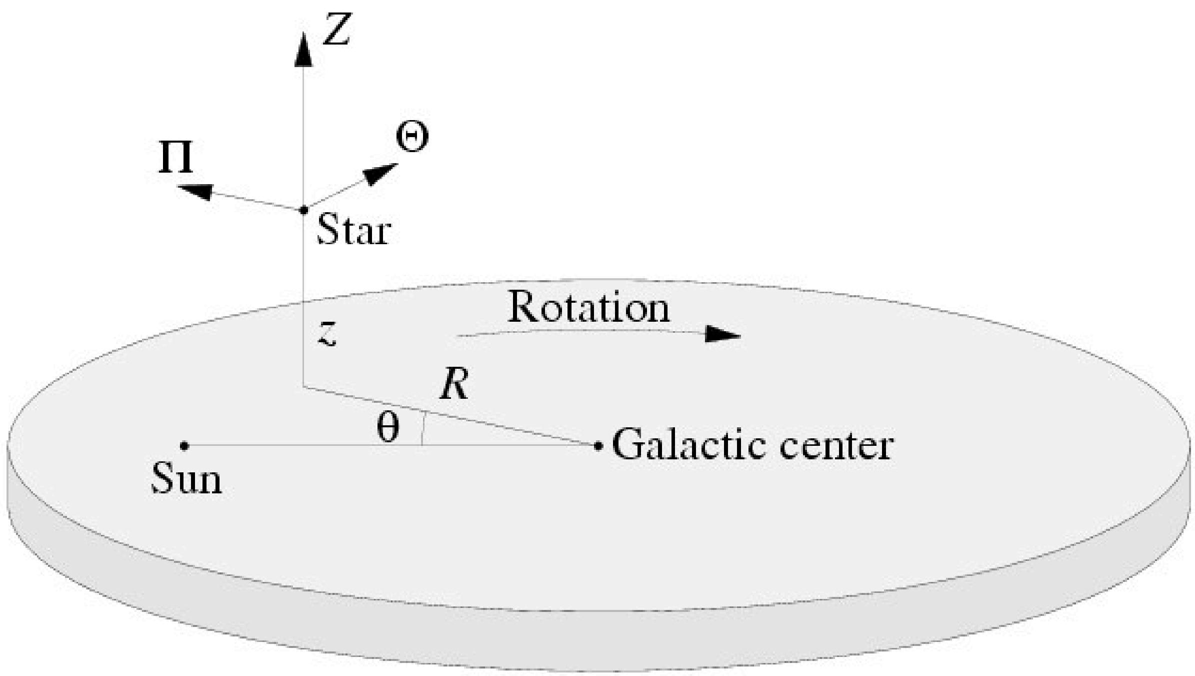
Kinematics of the Galaxy:
The Rotating, Cylindrical Coordinate System



$\Pi \equiv dR/dt$

$\Theta \equiv R\, d\theta/dt$

$Z \equiv dz/dt$



The Local Standard of Rest

- Defined as the point which co-rotates with the Galaxy at the solar Galactocentric radius
- Orbital speed of the LSR: $\Theta_{LSR} = \Theta_0 = 220$ km/s
- Define the peculiar velocity relative to the LSR as:

$$u = \Pi - \Pi_{LSR} = \Pi$$

$$v = \Theta - \Theta_{LSR} = \Theta - \Theta_0$$

$$w = Z - Z_{LSR} = Z$$

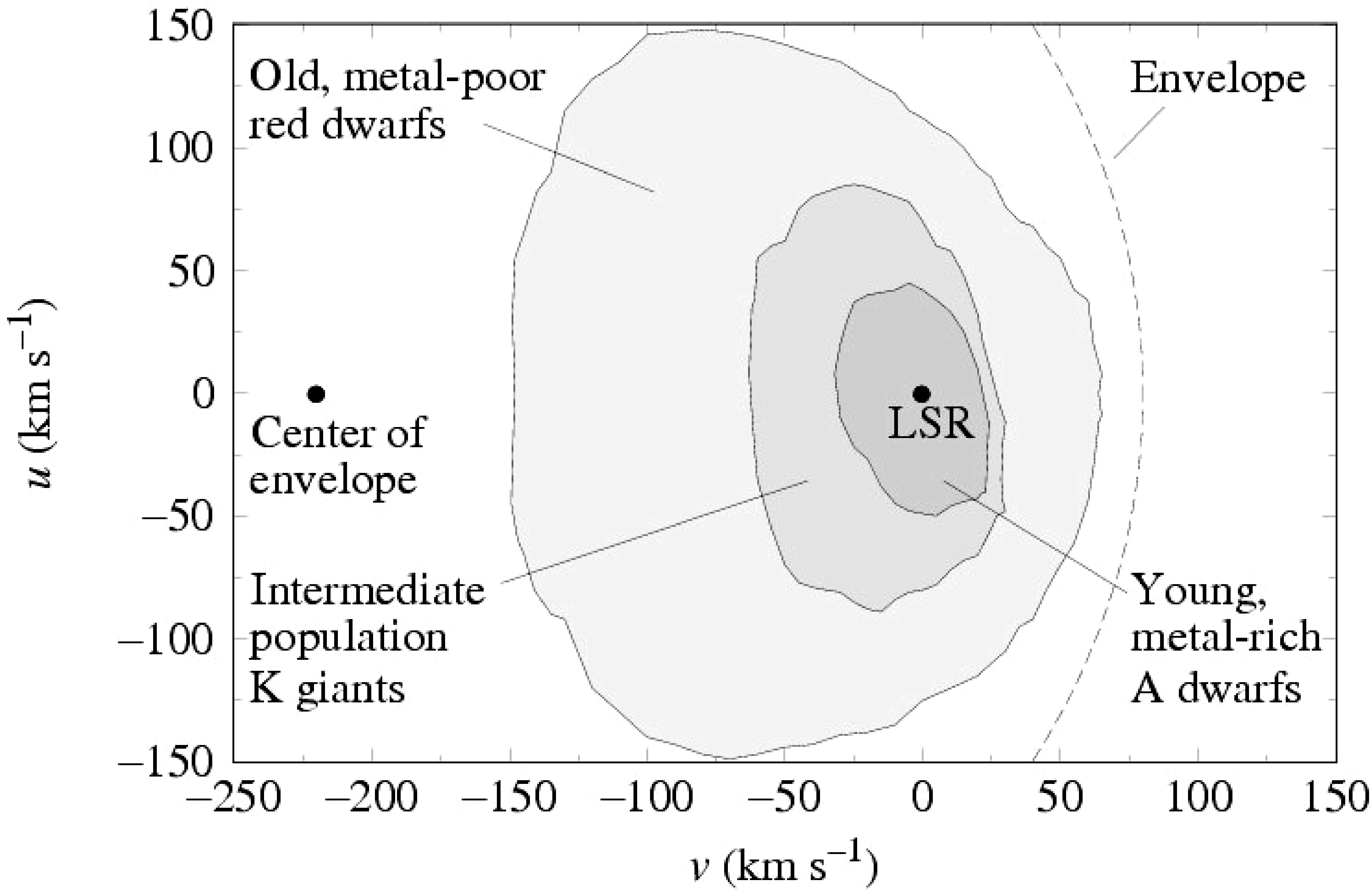
- The Sun's peculiar motion relative to the LSR:

$$u_\odot = -9 \text{ km/s}$$

$$v_\odot = +12 \text{ km/s}$$

$$w_\odot = +7 \text{ km/s}$$

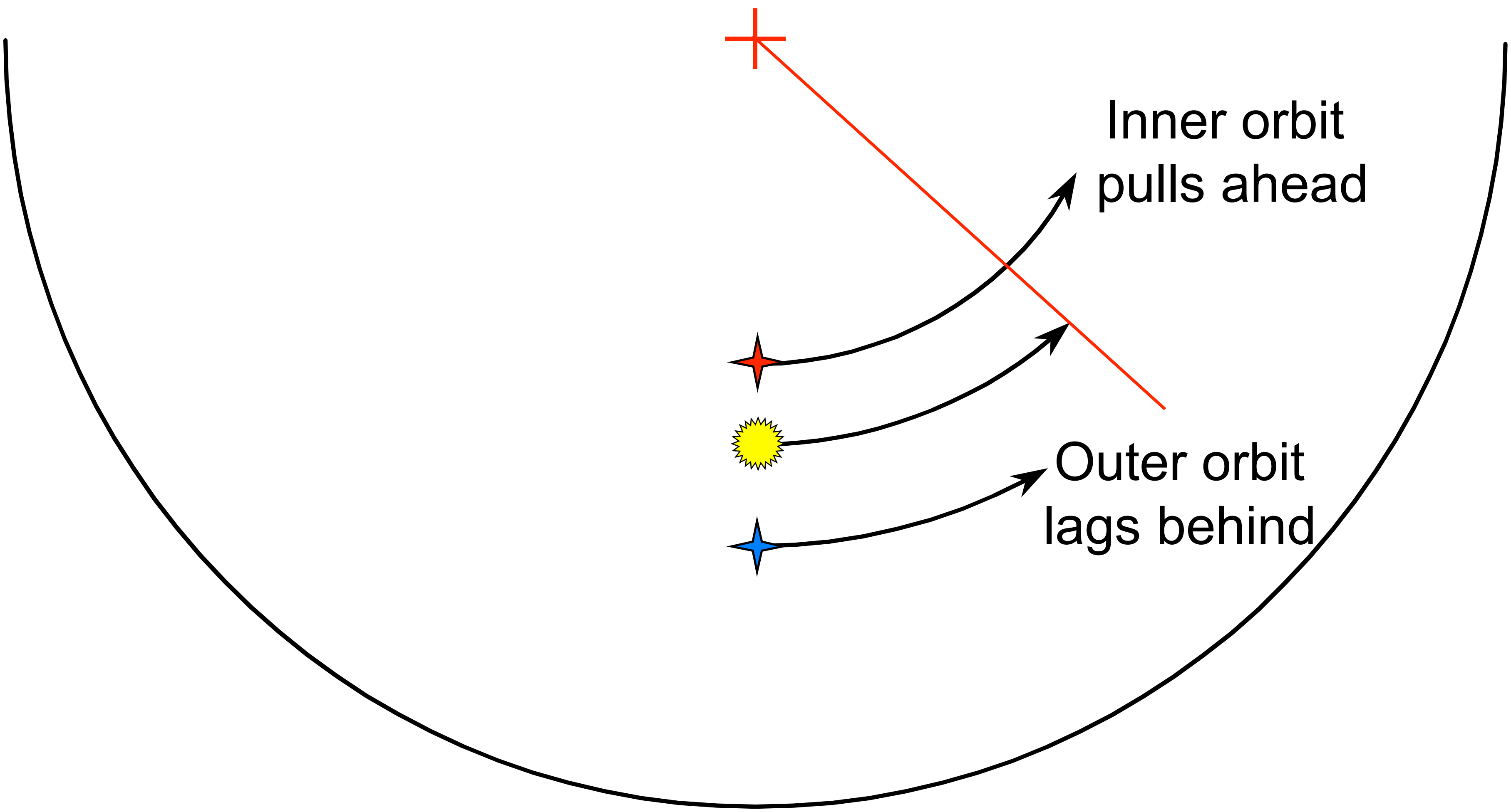
Stellar Kinematics Near the Sun



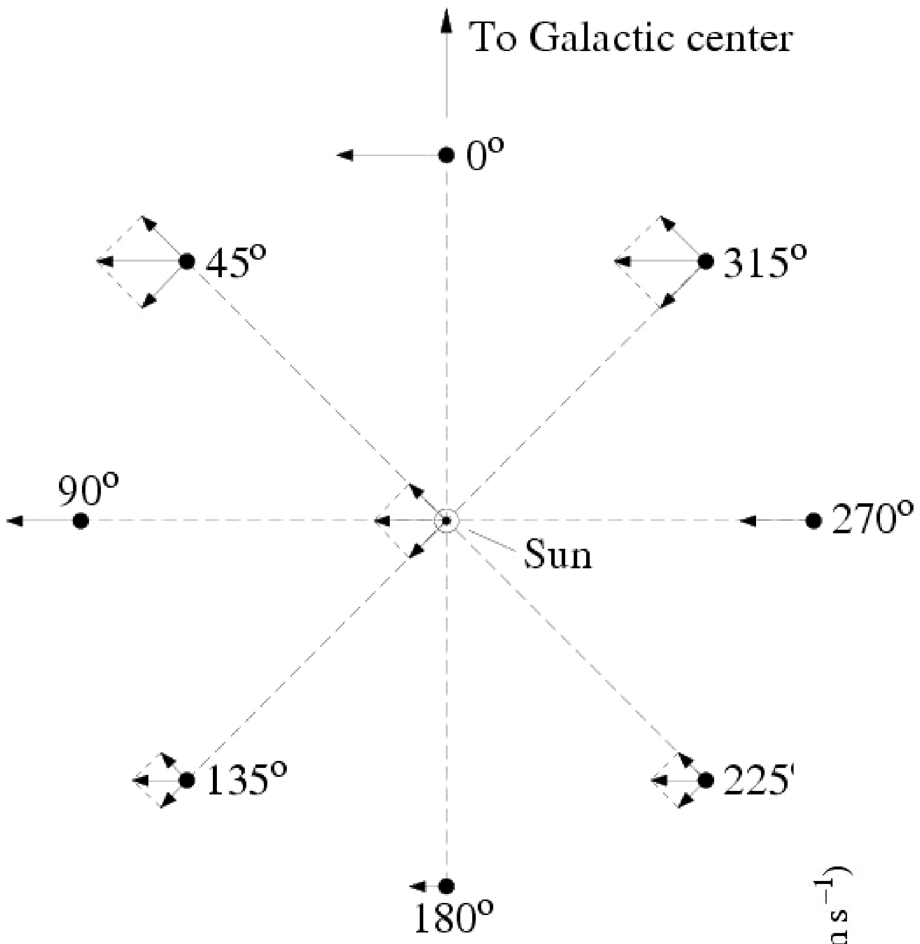
Stellar Kinematics Near the Sun

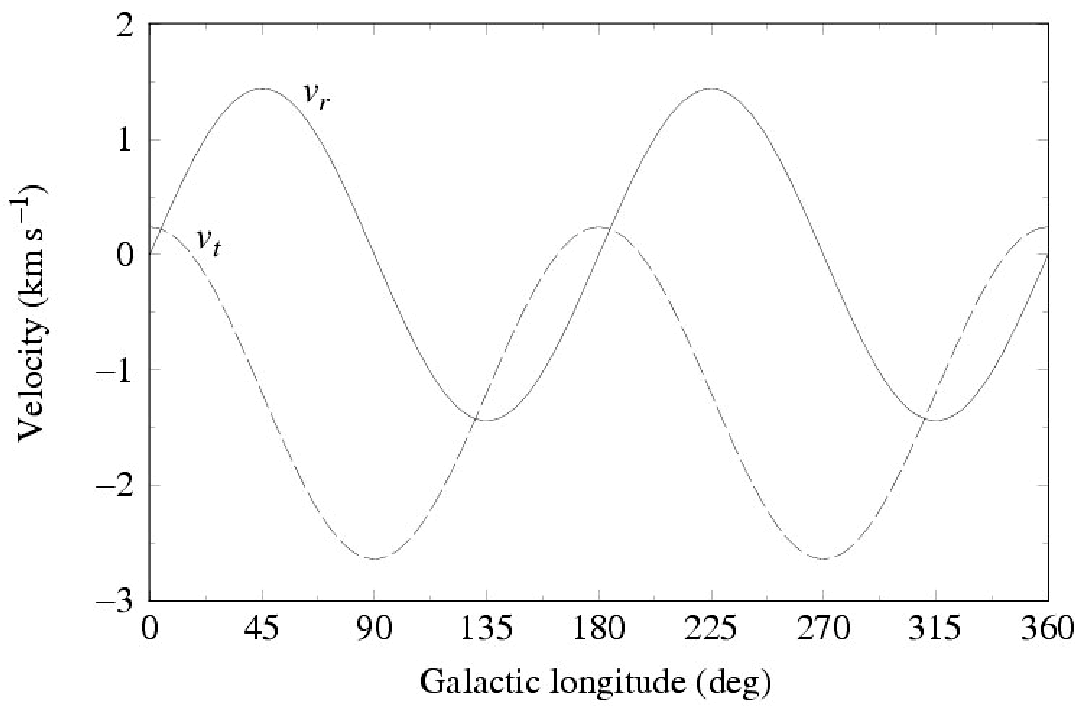
- Velocity dispersion of stars increases with their mean age: the evidence for a stochastic acceleration due to GMC and spiral arm encounters in a differentially rotating Galaxy
- The shape of the velocity ellipsoid also changes: older stars rotate more slowly; the thick disk rotates with a speed of about a half of that of the thin disk; and the halo does not seem to have a detectable rotation

Differential Rotation



The Appearance of Differential Rotation





Quantifying the Differential Rotation

The mean radial velocity v_r and proper motion μ of a group of stars at Galactic longitude ℓ and distance d from the sun is then

$$v_r = Ad\sin 2\ell, \quad \mu = A\cos 2\ell + B,$$

where the Oort constants A and B are given by

$$A \equiv \frac{1}{2}\left(\frac{\Theta}{R} - \frac{d\Theta}{dR}\right)_{R_o}, \quad B \equiv -\frac{1}{2}\left(\frac{\Theta}{R} + \frac{d\Theta}{dR}\right)_{R_o}.$$

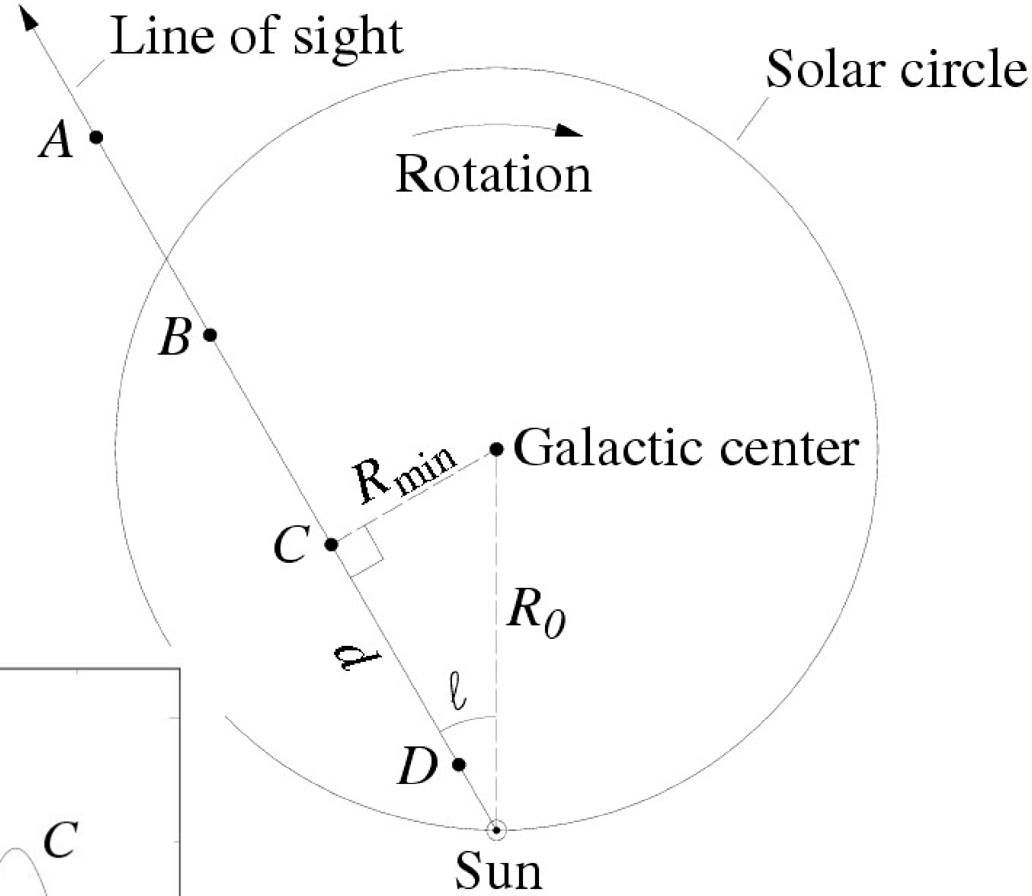
The values of the A and B constants, which measure the local shear and vorticity respectively, can be derived from local measurements of radial velocity and proper motion, and constrain the values of Θ_o, R_o, and $(d\Theta/dR)_{R_o}$.

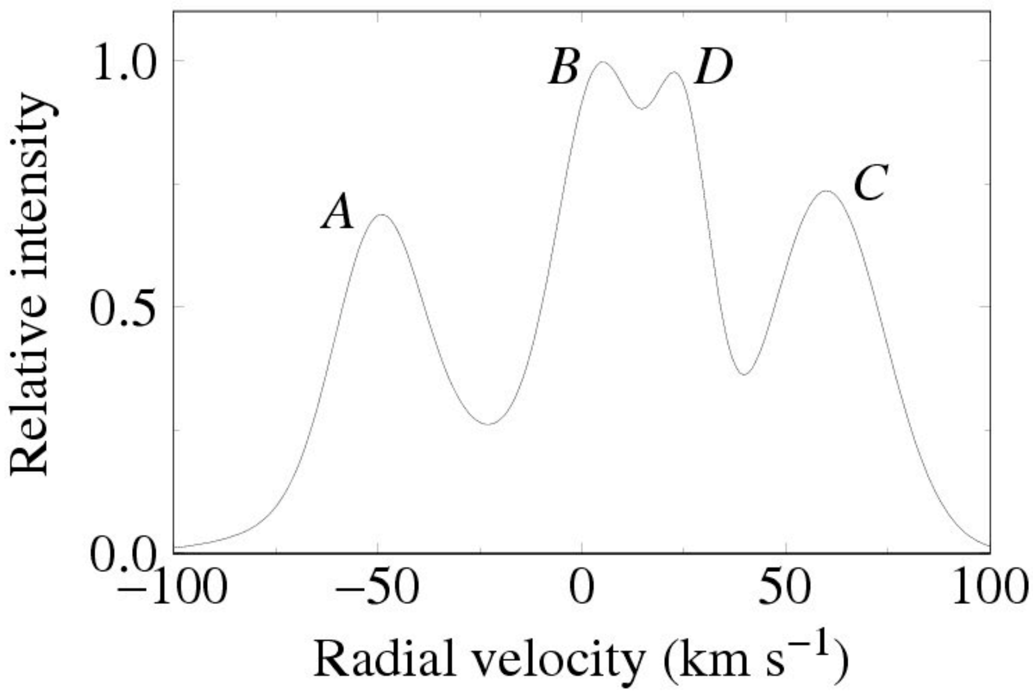
in a differentially rotating disk the radial velocity of an object relative to the LSR is given by

$$v_r = \left[\frac{\Theta(R)}{R} - \frac{\Theta_o}{R_o}\right] R_o \sin\ell, \qquad 3.$$

where $\Theta(R)$ is the circular velocity at the Galactocentric distance R of the object and ℓ is its Galactic longitude. Camm analyzed a sample of planetary

Thus, by measuring radial velocities, if we knew the distances, we could map out the differential rotation pattern

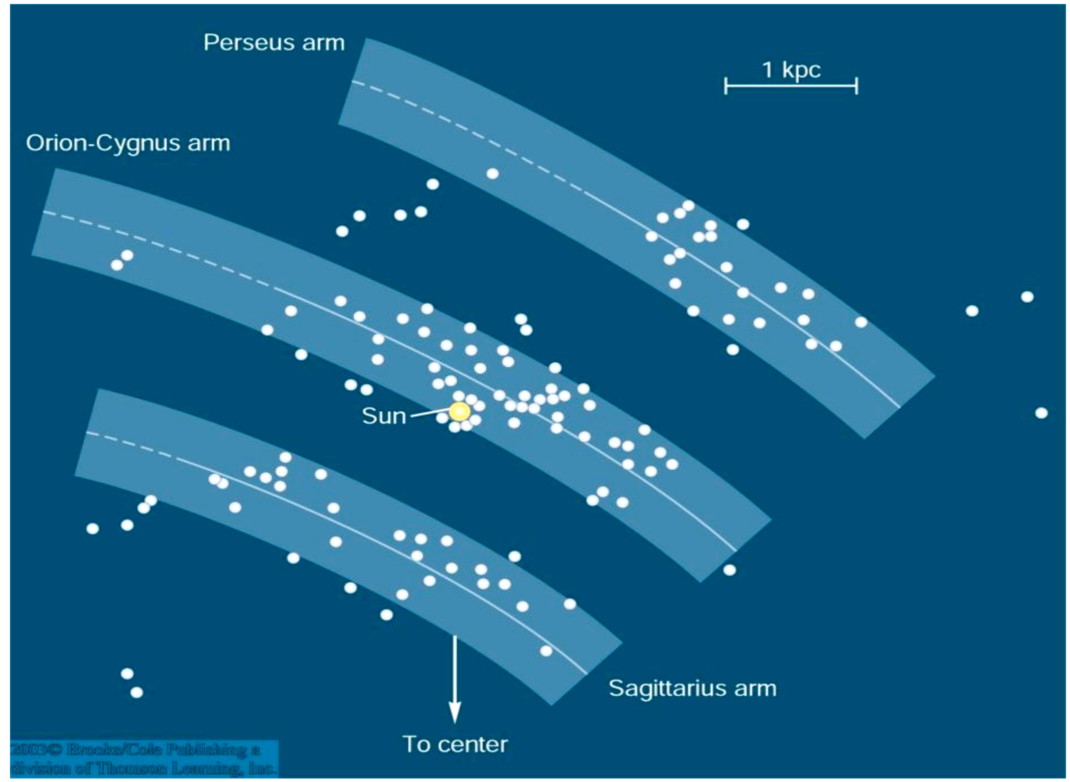




The trick, of course, is knowing the distances… Photometric distances to OB stars and young clusters are used.

Combining Distances and Velocities

- Since the spiral density waves concentrate the H I, and also may trigger star formation, we can associate young stars, OB associations and clusters with ISM peaks



- Since these stars must be young, they could not have moved very far relative to the gas
- Fortunately, they are also very bright and can be seen far away
- Of course, the extinction must be also understood very well

Gas Responds to the Spiral Density Wave Pattern, and the Rotating Bar

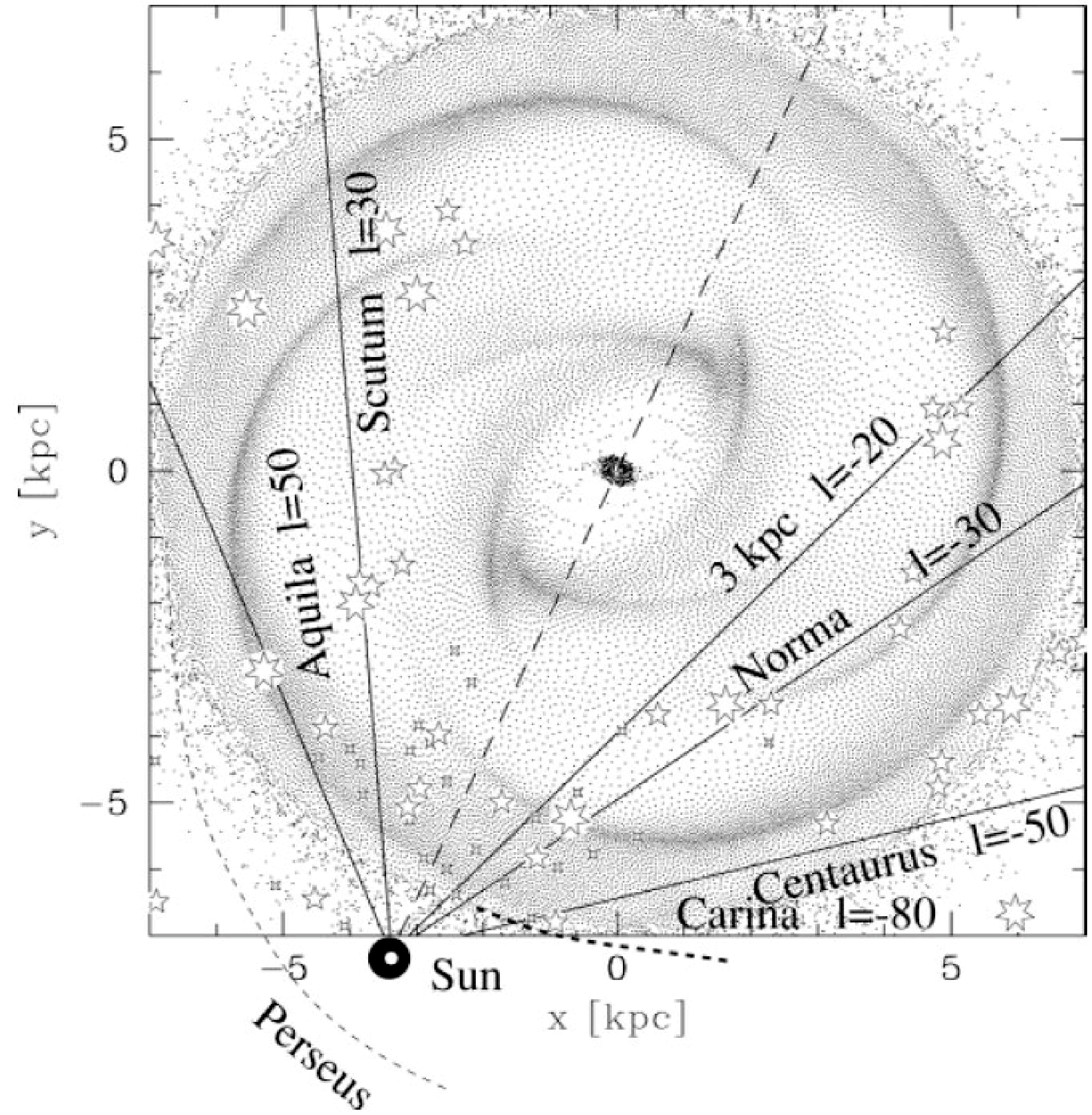


Figure 5. The gas flow in the Galactic disk under the influence of the barred bulge with a bar angle ϕ = 20º, corotation radius at ~3.1 kpc as well as a dark halo component (Englmaier and

… And the Result Is: A Flat Rotation Curve!

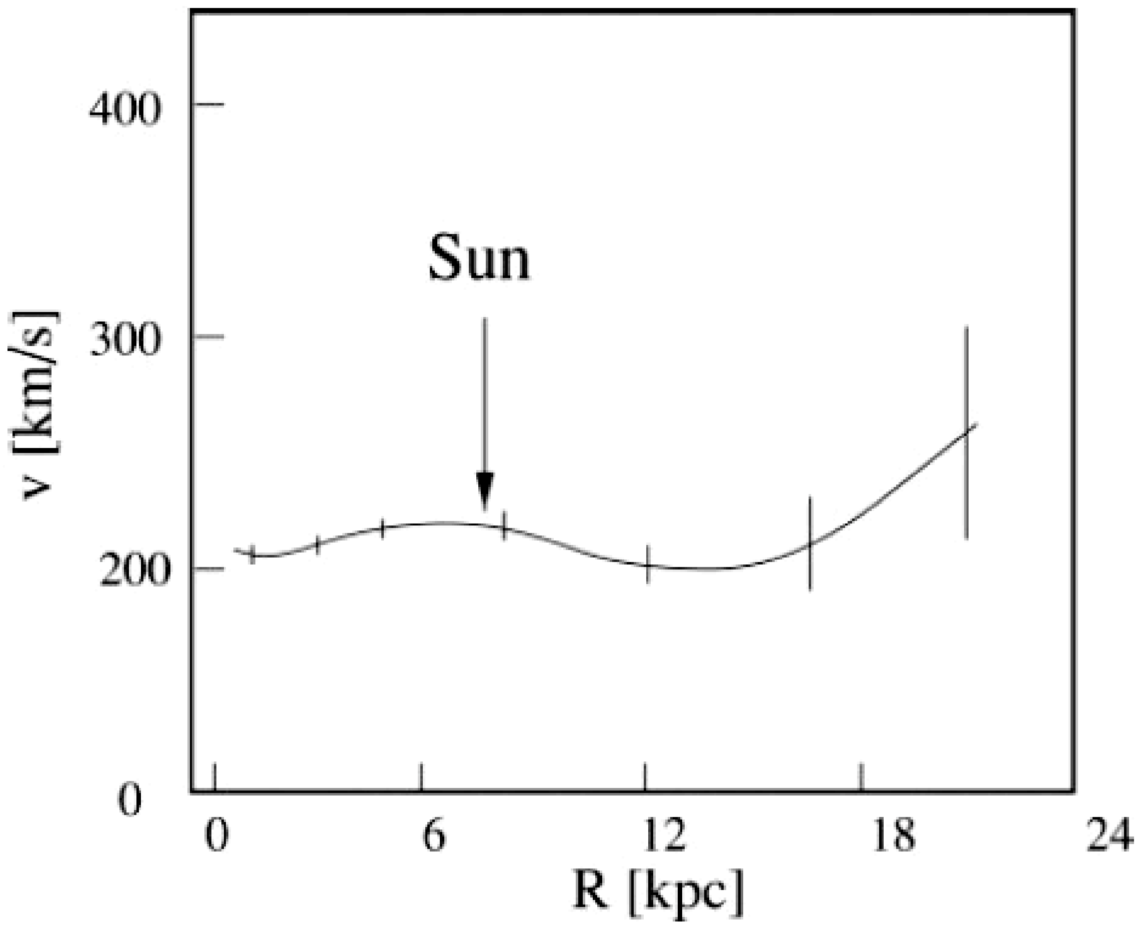
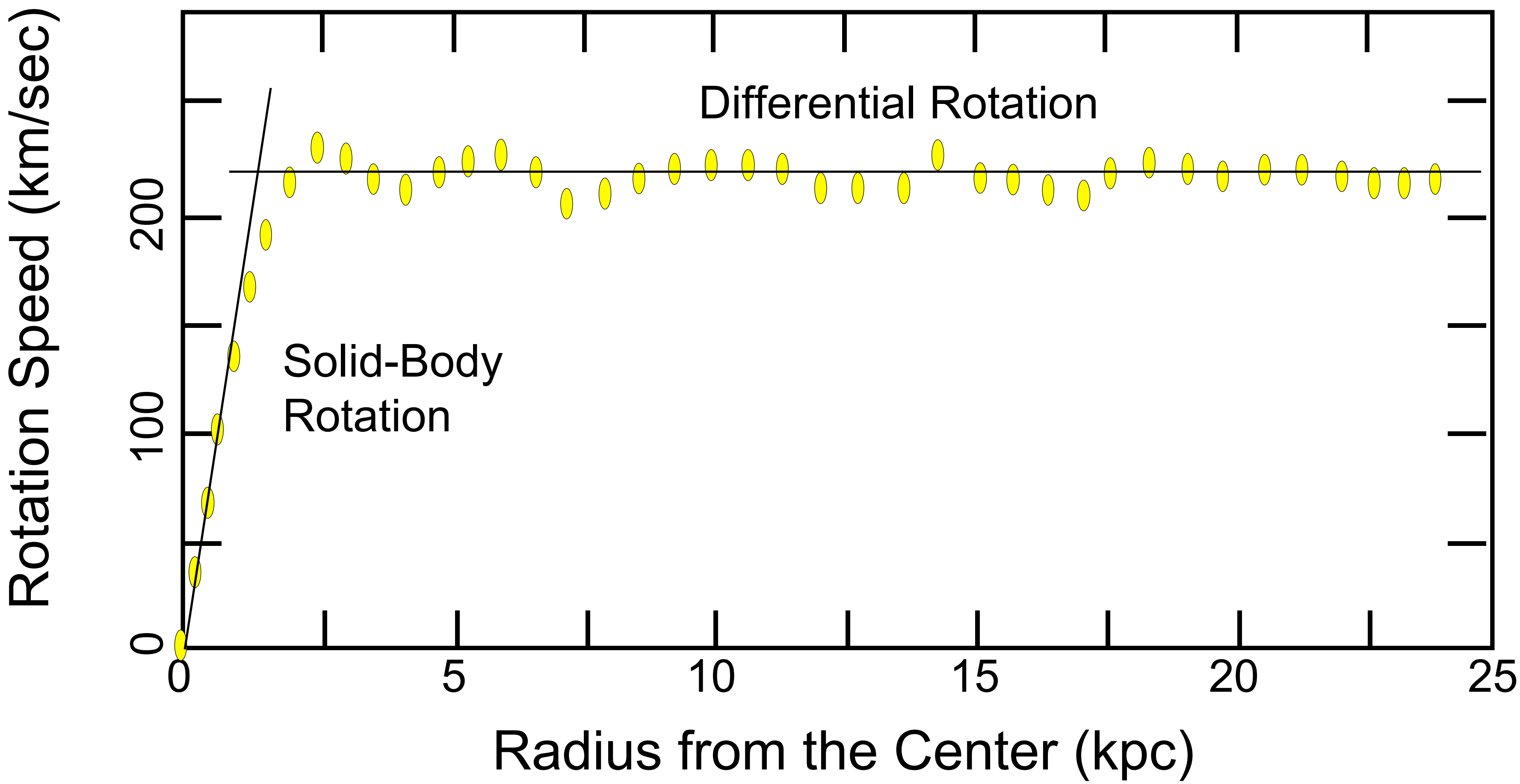


Figure 2. Rotation curve for the Galaxy (after Fich and Tremaine 1991). The vertical bars indicate the approximate uncertainty.

Schematic Spiral Galaxy Rotation Curve:

Very common, our Galaxy is not special in this regard



Interpreting the Rotation Curve

Motions of the stars and gas in the disk of a spiral galaxy are approximately circular (v_R and $v_z \ll v_\phi$).

Define the circular velocity at radius r in the galaxy as V(r). Acceleration of the star moving in a circular orbit must be provided by a net inward gravitational force:

$$\frac{V^2(r)}{r} = -F_r(r)$$

To calculate $F_r(r)$, must in principle sum up gravitational force from bulge, disk and halo.

If the mass enclosed within radius r is M(r), gravitational force is:

$$F_r = -\frac{GM(r)}{r^2}$$

Simple model predicts the rotation curve of the Milky Way ought to look like:

$$v \approx \sqrt{\frac{GM_{galaxy}}{R}} = 210 \left(\frac{M_{galaxy}}{8 \times 10^{10} M_{sun}}\right)^{1/2} \left(\frac{R}{8 \text{ kpc}}\right)^{-1/2} \text{ km s}^{-1}$$

This number is about right - Sun's rotation velocity is around 200 km s^{-1}.

Scaling of velocity with $R^{-1/2}$ is not right - actual rotation velocity is roughly constant with radius.

Implies:

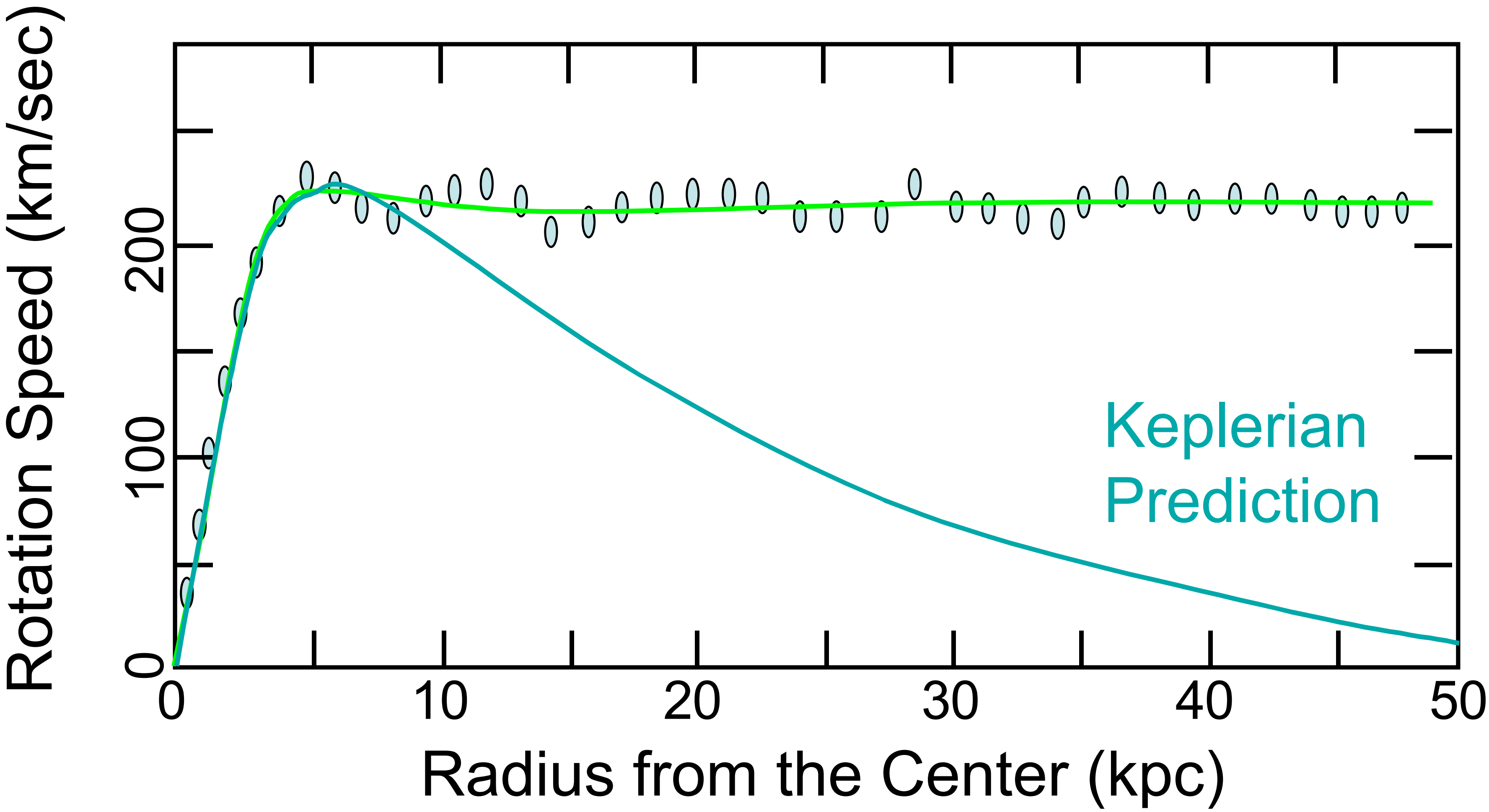
- gravity of visible stars and gas largely explains the rotation velocity of the Sun about the Galactic center.
- Flat rotation curve requires extra matter at larger radii, over and above visible components.

⇒ **Dark matter…**

(From P. Armitage)

Observed *vs*. Predicted Keplerian

(from the visible mass only)



Mass Distribution in a Uniform Sphere:

If the density ρ is constant, then:

$$M(r) = \frac{4}{3}\pi r^3 \rho$$

$$V(r) = \sqrt{\frac{4\pi G\rho}{3}}\, r$$

Rotation curve rises linearly with radius, period of the orbit $2\pi r / V(r)$ is a constant independent of radius.

Roughly appropriate for central regions of spiral galaxies.

(From P. Armitage)

Power law density profile:

If the density falls off as a power law:

$$\rho(r) = \rho_0 \left(\frac{r}{r_0} \right)^{-\alpha}$$

…with $\alpha < 3$ a constant, then:

$$V(r) = \sqrt{\frac{4\pi G \rho_0 r_0^\alpha}{3 - \alpha}} r^{1-\alpha/2}$$

For many galaxies, circular speed curves are approximately flat (V(r) = constant). Suggests that mass density in these galaxies may be proportional to r^{-2}.

(From P. Armitage)

Simple model for a galaxy with a core:

Spherical density distribution:

$$4\pi G\rho(r) = \frac{V_H^2}{r^2 + a_H^2}$$

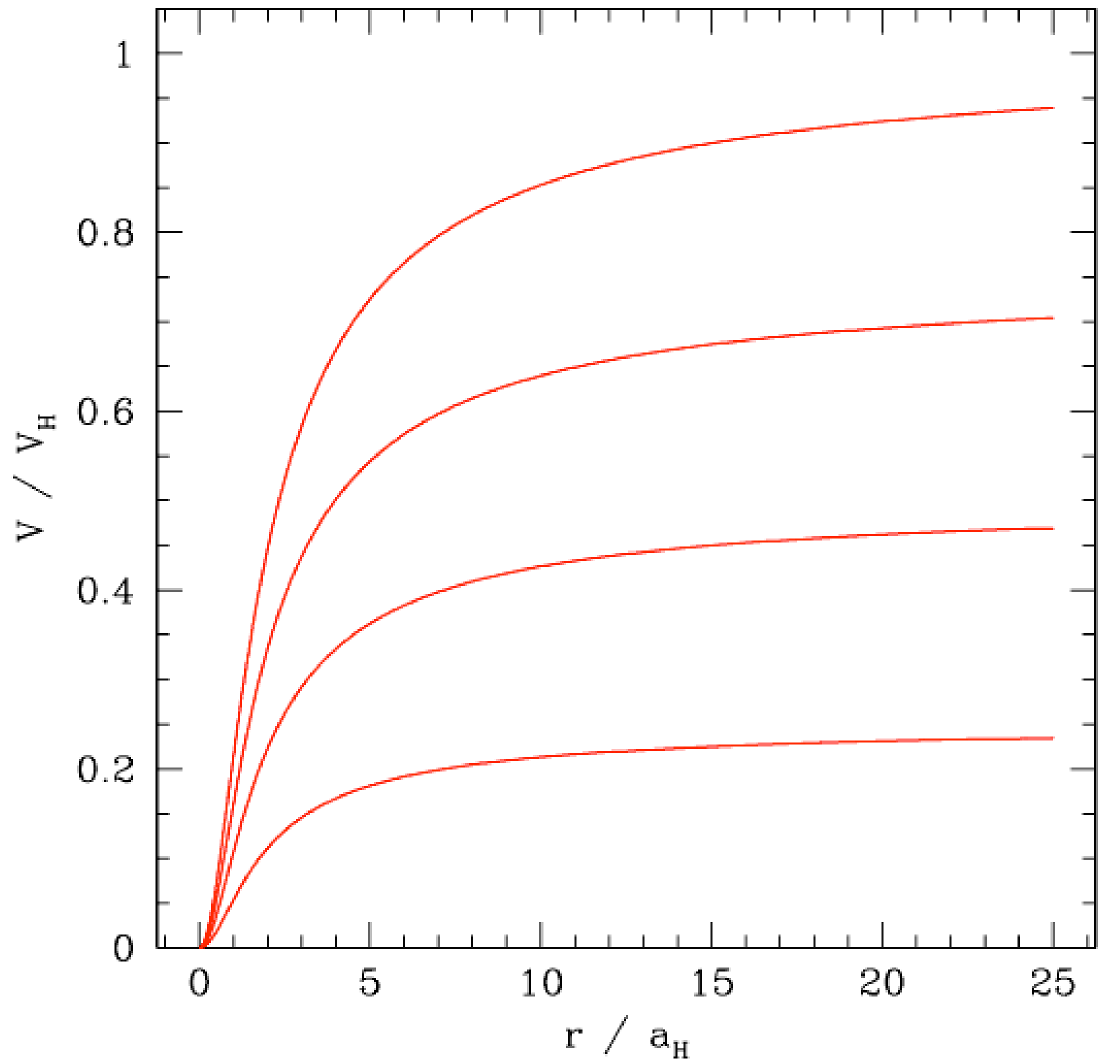
- Density tends to constant at small r
- Density tends to r^{-2} at large r

Corresponding circular velocity curve is:

$$V(r) = V_H \sqrt{1 - \frac{a_H}{r} \arctan\left(\frac{r}{a_H}\right)}$$

(From P. Armitage)

Resulting rotation curves:



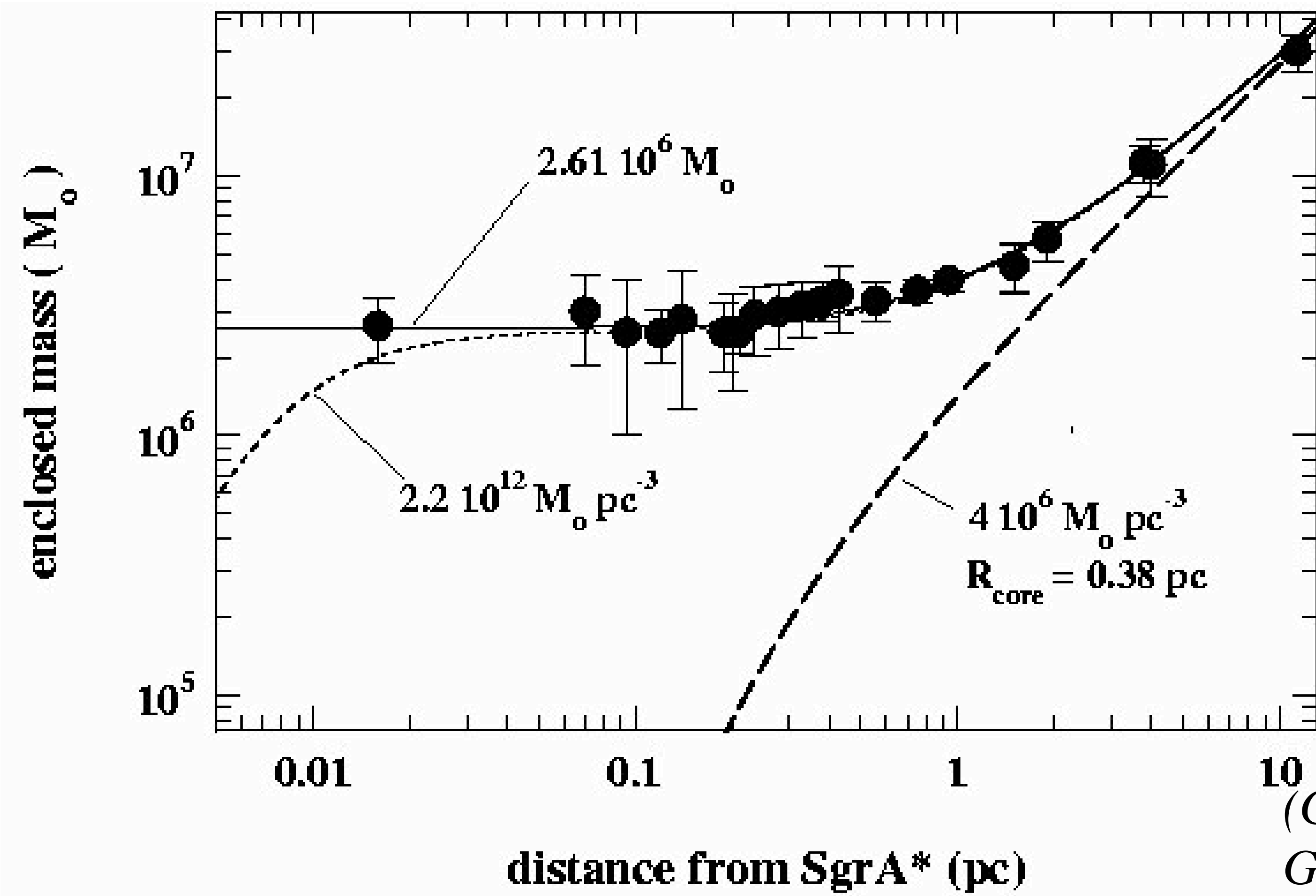
Not a bad representation of the observed rotation curves …

(From P. Armitage)

Now Let's Go To The Galactic Center …

Go to
http://www.astro.ucla.edu/~jlu/gc/journey/

Dynamical Evidence for a Supermassive Black Hole at the Galactic Center



(Genzel et al., Ghez et al.)

Note: R_S ($M_\bullet = 2.6 \times 10^6\ M_\odot$) $= 7.8 \times 10^8$ cm $= 6.5 \times 10^{-8}$ arcsec