• Atomic hydrogen can be mapped via the 21cm (1420 MHz) spin-flip transition in the radio. This hyperfine transition [`sketch it!`] is used to map galactic rotation curves. It reveals that neutral hydrogen gas (and IR measures of dust) are more tightly confined to the plane of the disk, with a scale height of 90pc.

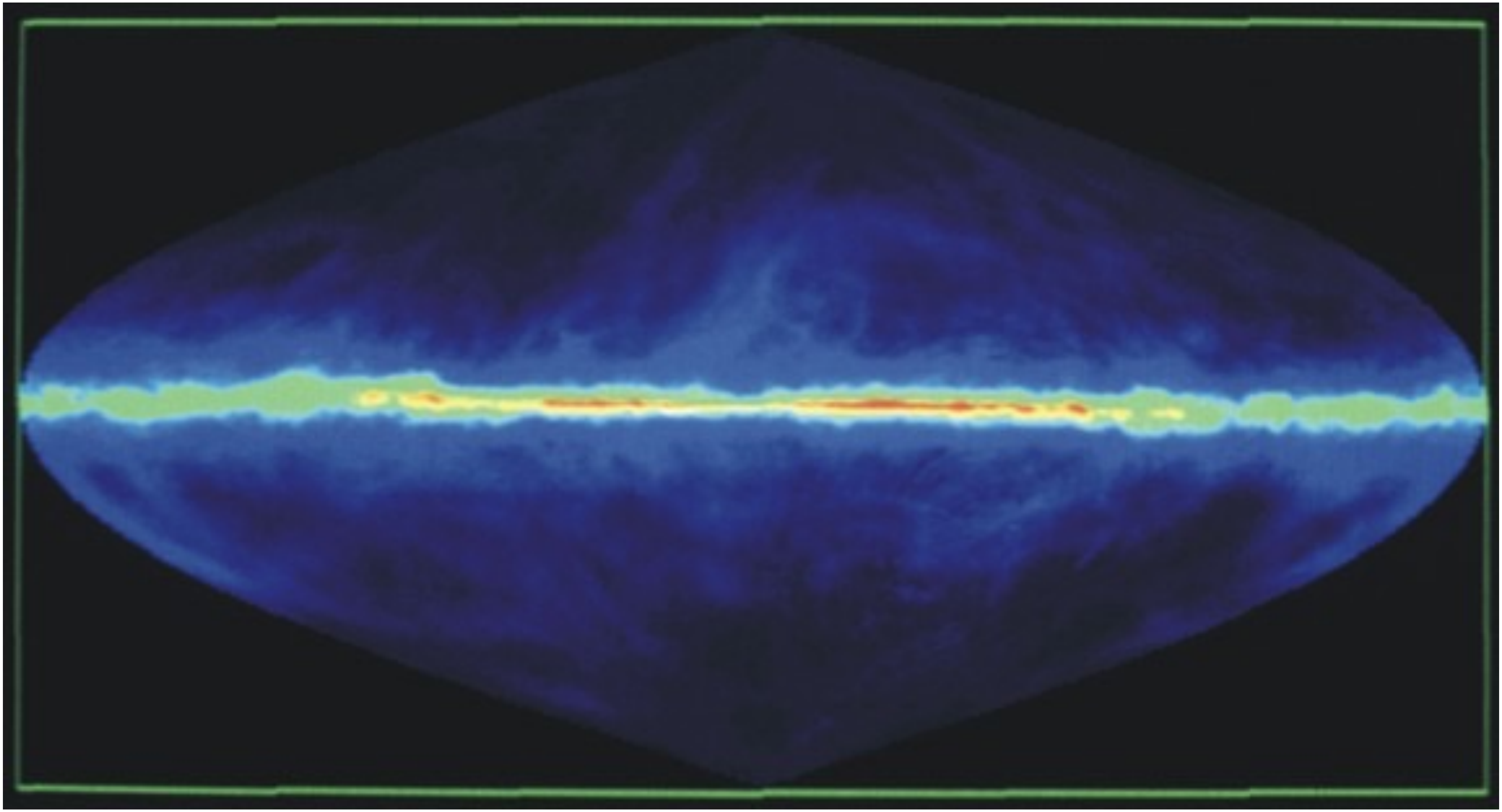
**Plot:** 21cm map of the Milky Way

Selecting the 21cm emission from distances greater than 15 kpc, using coupling to the rotational velocity dispersion, reveals clear evidence of a **warp** of the disk. This may be an indication of a past tidal interaction with neighboring galaxies.

• At high Galactic latitudes, the HI mapping reveals the existence of high velocity clouds, the majority of which possess large, negative line-of-sight velocities of 400 km/sec or more. This indicates that they are moving towards the disk, and so have spawned a **galactic fountain** model.

• HI maps also reveal the **Magellanic Stream**, a "trail" of clouds behind the LMC and SMC. This suggests the influence of a tidal interaction in galaxy collisions some 200 million years ago.

# 21cm HI Map of the Milky Way



• The disk flares near the Galactic Center, to form the **Galactic bulge**. The surface intensity profile of the bulge is given by the famous $r^{1/4}$ law of de Vaucouleurs (1948), which is frequently applied to elliptical galaxies:

$$\boxed{\log_{10} \frac{I(r)}{I_e} \;=\; -\frac{10}{3}\left\{ \left(\frac{r}{r_e}\right)^{1/4} - 1 \right\} \quad .} \tag{8}$$

Here $r_e$ is the effective radius of the bulge, which in the IR is determined to be about 0.7kpc. The bulge is not spherical, and may resemble a **bar**, so that $I(r)$ represents a projection of the geometry. It is also not homogeneous, and has "holes" such as **Baade's window** (1944) that permit a view through to the other side of the Galaxy.

• The halo above the disk possesses interesting components. The first consists of field stars and **globular clusters** (GCs), which possess typically $10^5 - 10^6$ stars. The high-latitude GCs are very old (10-13 Gyr; *these values are impacted by the WMAP and Planck CMB determinations*) and typically metal-poor, though there is a metal-rich component confined to near the Galactic plane.

**C & O, pp. 894-98**

**Plot:** Globular Cluster Spatial Distributions

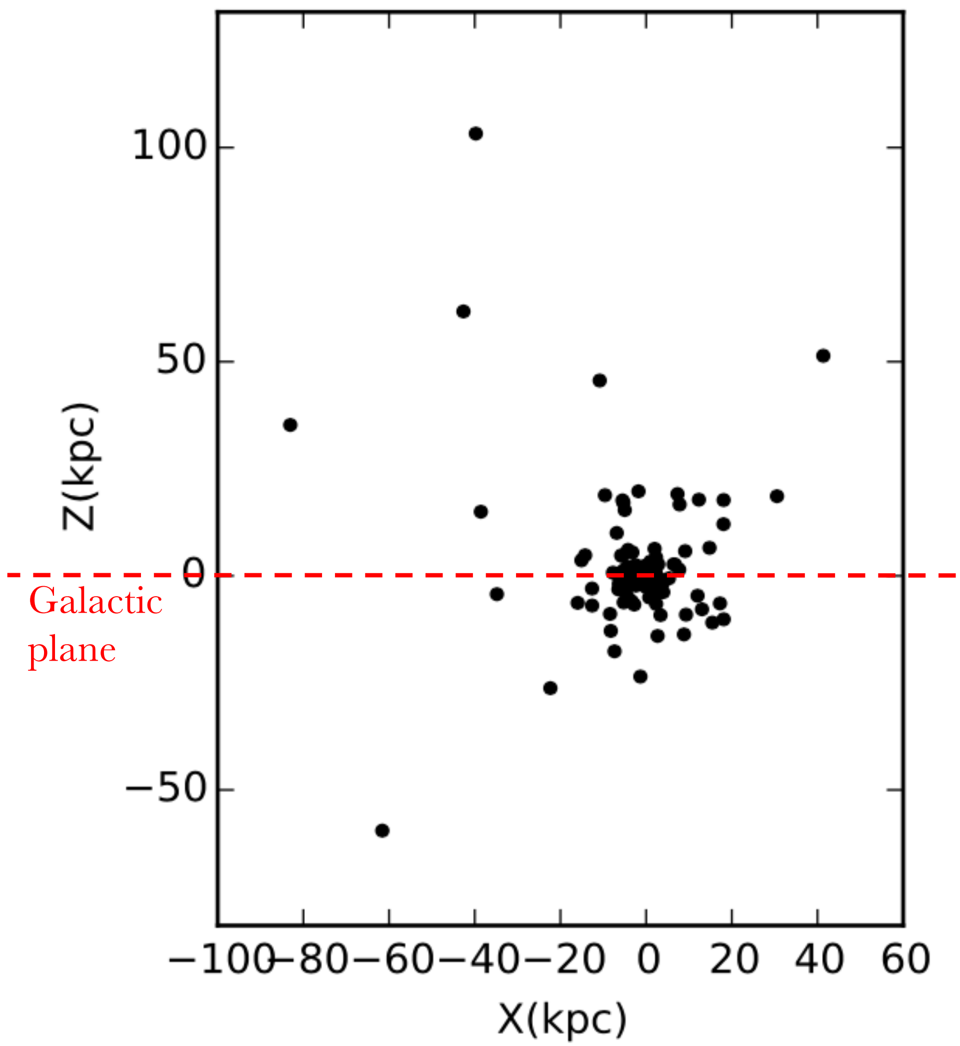
∗ There are over 160 known GCs, most found within 40kpc of the Galactic Center, with a handful in the 50–150kpc range. Assuming a spherical cloud for these most distant ones, with them being tied to the gravity of dark matter, can deliver constraints on the position of the Galactic Center.

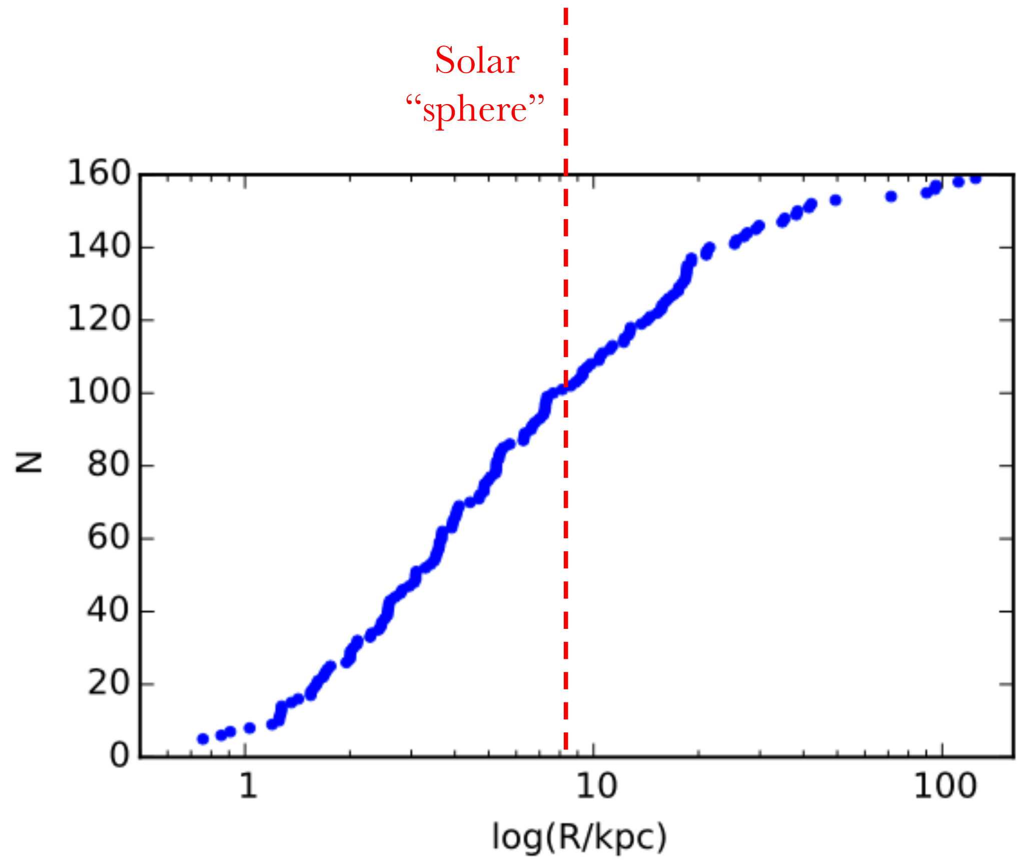
• A major component of the halo is the Galactic magnetic field, which is chaotic and of a typical strength less than $4\mu$ Gauss (the value in the disk). Its value is difficult to measure, though some information on its directionality can be gleaned from polarized radio emission from dust grains.

∗ The magnetic field is responsible for trapping Galactic cosmic rays (relativistic ions), and deflecting incoming UHECRs.

• The last major component of the halo concerns **dark matter**, which we will consider at length shortly.

# Globular Cluster Spatial Distribution




- *Left*: projection of globular cluster (GC) distribution onto (X,Z) plane, with the sun lying at (-8.34,0,0) kpc. The disk lies in the (X,Y) plane with Z being the pole.
- *Top right*: cumulative number N of GCs with distance R from the Galactic Center.
- Arakelyan et al. (2018, MNRAS **481**, 918).

# 3 Kinematics of the Milky Way

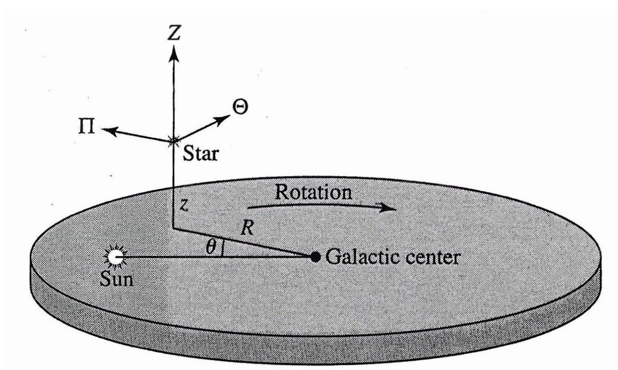
The Galactic Coordinate System is tilted with respect to celestial coordinates, but is analogous in terms of its variables and polar directions. Transformations from RA and Dec coordinates are outlined in Carroll & Ostlie. **C & O, Sec. 24.3**

[*Reading Assignment: Transformations to Galactic coordinates, pp. 899–901*]

**Plot:** Galactic Coordinate System Essentials and Variables

Cylindrical coordinates $(R, \theta, z)$ are adopted for Galactic considerations, with velocity components being labelled

$$\Pi \equiv \frac{dR}{dt} \quad , \quad \Theta \equiv R\frac{d\theta}{dt} \quad , \quad Z \equiv \frac{dz}{dt} \quad . \tag{9}$$



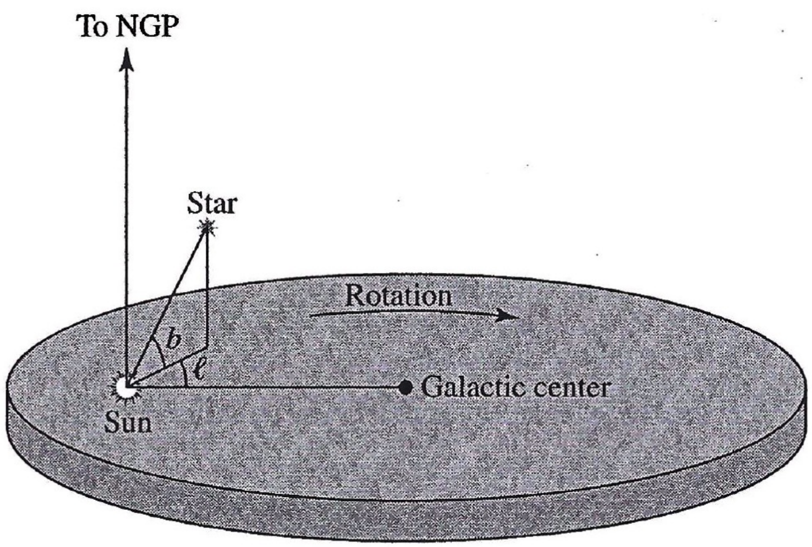

The cylindrical coordinates used to analyze Galactic kinematics

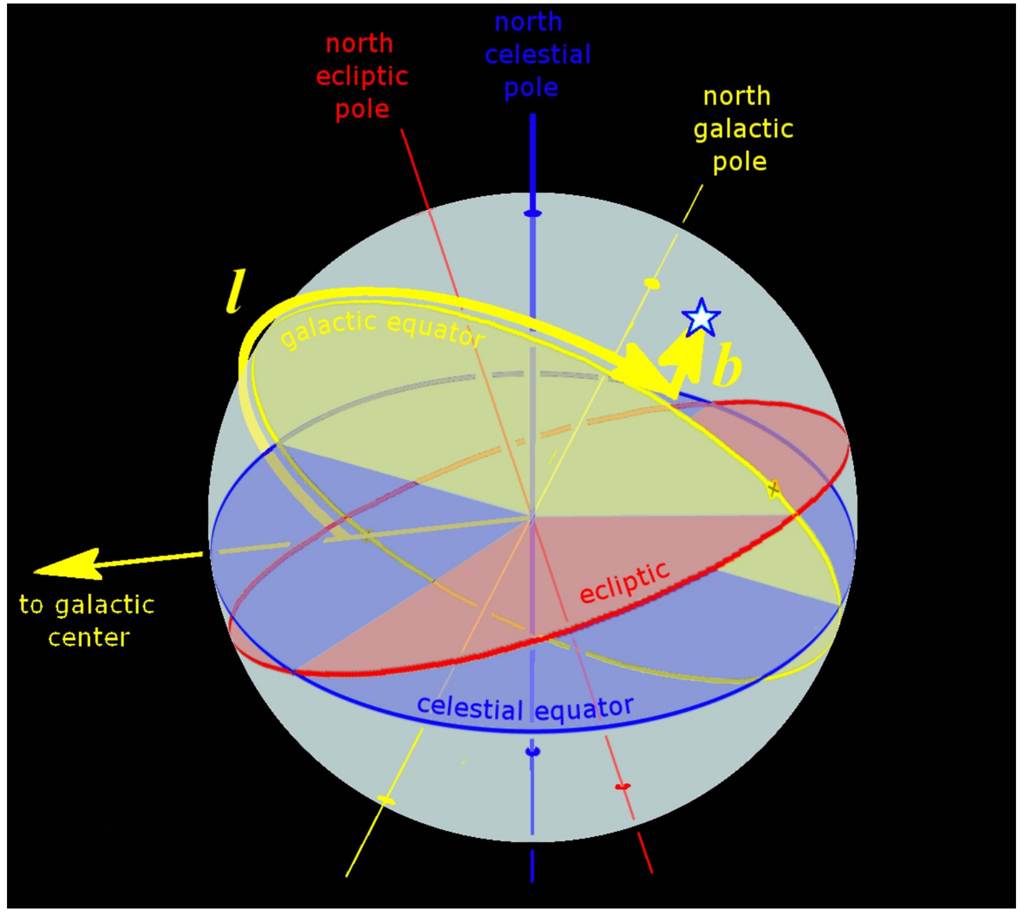
• The sun's **peculiar motion** must be extracted, to define a **dynamical local standard of rest** (LSR), which is a point instantaneously at the position of the sun that moves in a *perfectly circular orbit* about the Galactic Center. This is close to the **kinematic** LSR, which is based on the average motions of nearby stars. By definition,

$$\Pi_{\rm LSR} \equiv 0 \quad , \quad \Theta_{\rm LSR} \equiv \Theta_0 \quad , \quad Z_{\rm LSR} \equiv 0 \quad . \tag{10}$$

The velocity of a star relative to the LSR is known as the star's **peculiar velocity**. Since the LSR is not defined by the solar motion, the sun moves

# Galactic and other Coordinate Systems




- *Left*: the definition of Galactic coordinates, latitude *b* and longitude *l*. Fig. 24.17 of Carroll & Ostlie.
- *Right*: the relative orientations of the Galactic coordinate system (yellow) to the ecliptic (red) and celestial coordinates (α, δ; blue). From Wikipedia.

relative to the LSR , and using ensembles of stars, it is found that the *solar peculiar velocity* has components

$$\begin{aligned} \Pi_\odot &= -10.0 \pm 0.4 \text{ km sec}^{-1} \\ \Theta_\odot - \Theta_{0,\odot} &= 5.2 \pm 0.6 \text{ km sec}^{-1} \\ Z_\odot &= 7.2 \pm 0.4 \text{ km sec}^{-1} \quad , \end{aligned} \tag{11}$$

also known as the $(u, v, w)$ velocity components of the sun.

• Stars do not move in circles around the GC, but rather in ellipses (with an identifiable **apogalacticon** and **perigalacticon**) until they engage in a close encounter that deflects their orbit. Such encounters **stochasticize** their velocities, so that they **virialize** at a "temperature" appropriate to their local galactic gravitational potential, i.e. at $\sim 10\,\text{km/sec}$ for the sun.

∗ Localized populations of stars therefore possess a **velocity dispersion** $\sigma$ (standard deviation) in each of their velocity distribution components:

$$\sigma_\Pi = \sqrt{\langle \Pi^2 \rangle} \quad , \quad \sigma_\Theta = \sqrt{\langle \Theta^2 \rangle} \quad , \quad \sigma_Z = \sqrt{\langle Z^2 \rangle} \quad . \tag{12}$$

Multiplying these by typical masses $\sim 0.3 - 20 M_\odot$ gives kinetic energies that, by the **virial theorem**, are half the total gravitational potential of the galaxy "interior" to their location [sketch a diagram].

• Based on determinations of peculiar velocities in the **solar neighbourhood**, it appears that the orbital speed of the LSR is

$$\Theta_0 \approx 220 \text{ km sec}^{-1} \quad , \tag{13}$$

though this IAU-accepted standard may be too large.

**Plot:** Peculiar Velocities in the Solar Neighbourhood

• The orbital period of the LSR, using $R_0 = 8.5\,\text{kpc}$, is

$$P_{LSR} = \frac{2\pi R_0}{\Theta_0} = 237 \text{ Myr} \quad . \tag{14}$$

The central galactic mass that would induce such a rotational period, assuming Kepler's Third Law, is

$$M_{<8.5\text{kpc}} = \frac{4\pi^2 R_0^3}{G\, P_{LSR}^2} \equiv \frac{R_0 \Theta_0^2}{G} \sim 9.6 \times 10^{10}\, M_\odot \quad . \tag{15}$$

# Peculiar Velocities: Solar Neighbourhood

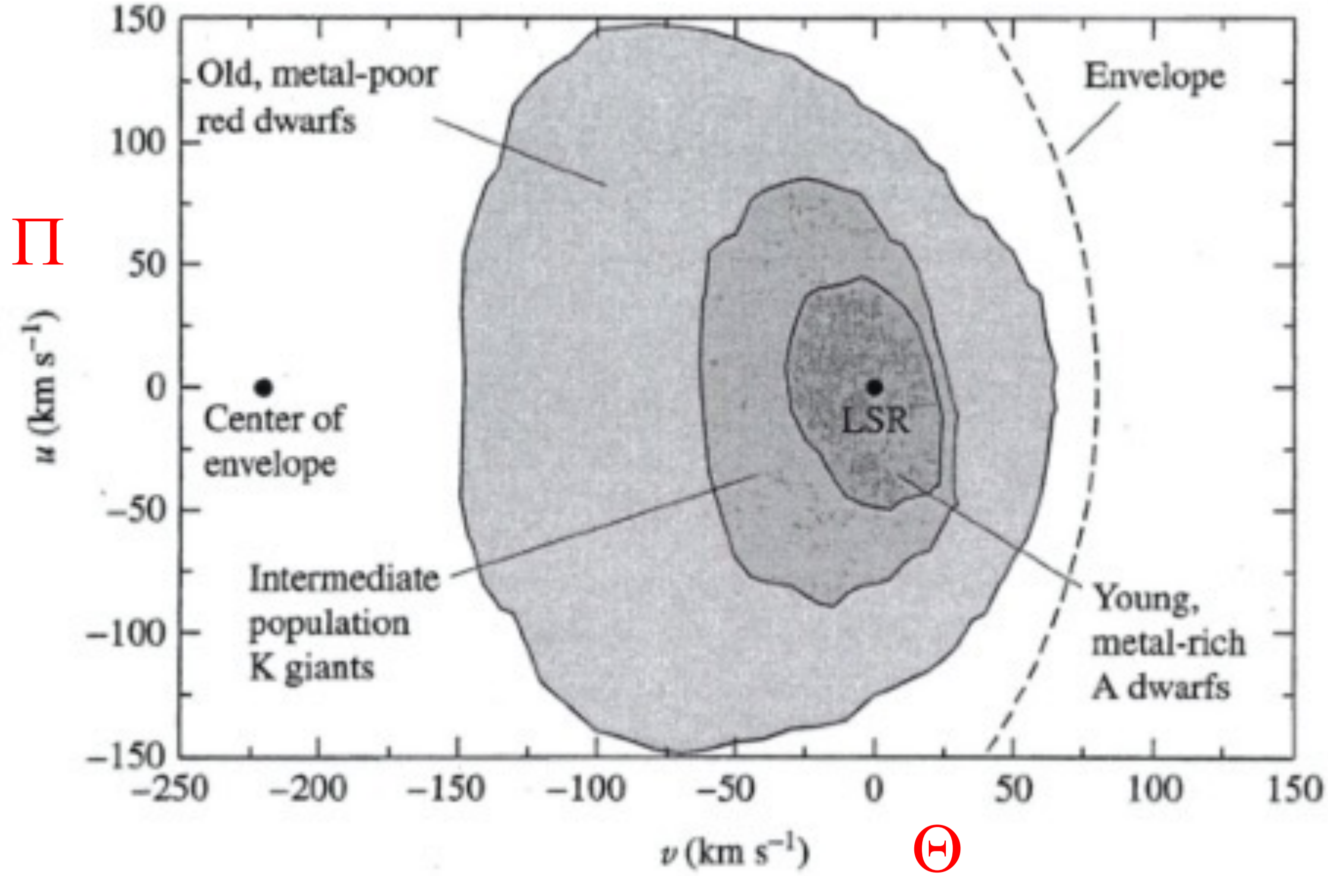



**FIGURE 24.21** A schematic diagram of the peculiar velocity components $v$ and $u$ for stars in the solar neighborhood. The innermost contour represents metal-rich main-sequence A stars, the middle contour depicts older K giants, and the outer contour indicates very metal-poor red dwarfs. The LSR is located at $(v, u) = (0, 0)$. An enveloping circle with an approximate radius of 300 km $s^{-1}$ and centered at $v = -220$ km $s^{-1}$ reveals the orbital velocity of the LSR.