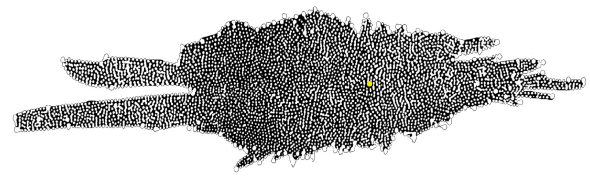
Astronomy 330

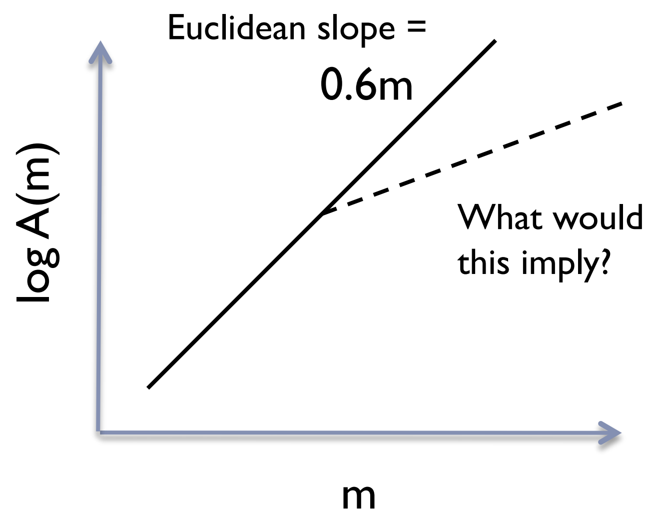
Lecture 7

24 Sep 2010

Outline

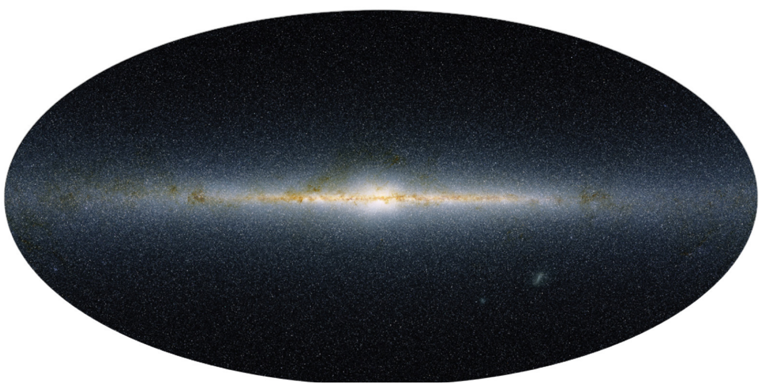
- Review
  - Counts: A(m), Euclidean slope, Olbers' paradox
  - Stellar Luminosity Function: Φ(M,S)
  - Structure of the Milky Way: disk, bulge, halo
- Milky Way kinematics
  - Rotation and Oort's constants
  - Solar motion
  - Disk vs halo
  - An example

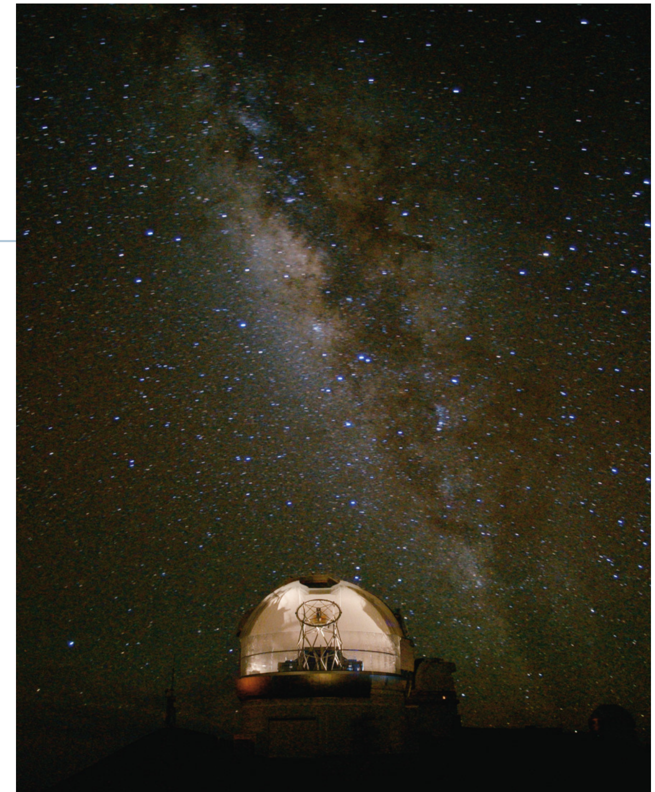


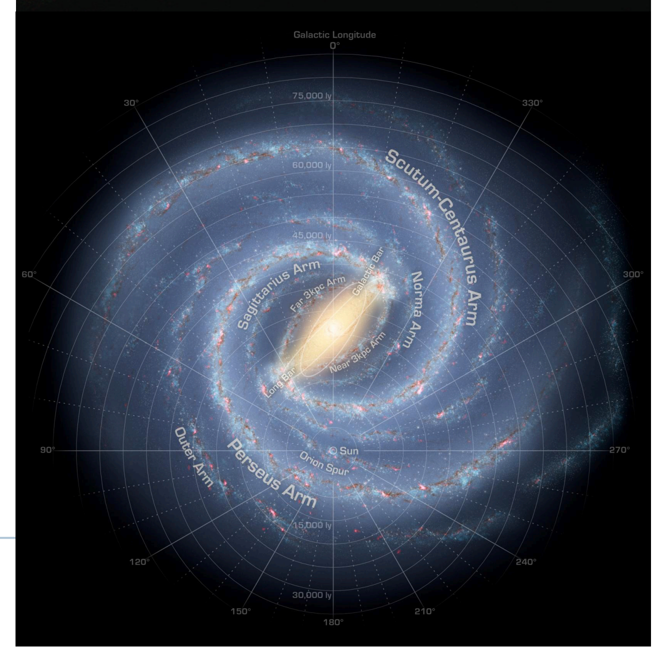


Review: Galactic structure

- Stellar Luminosity Function: Φ
  - What does it look like?
  - How do you measure it?
  - What's Malmquist Bias?
- Modeling the MW
  - Exponential disk: $\rho_{disk} \sim \rho_0 \exp(-z/z_0 - R/h_R)$
    - (radially/vertically)
  - Halo – $\rho_{halo} \sim \rho_0 r^{-3}$
    - (RR Lyrae stars, globular clusters)
  - See handout – Benjamin et al. (2005)
- Galactic Center/Bar

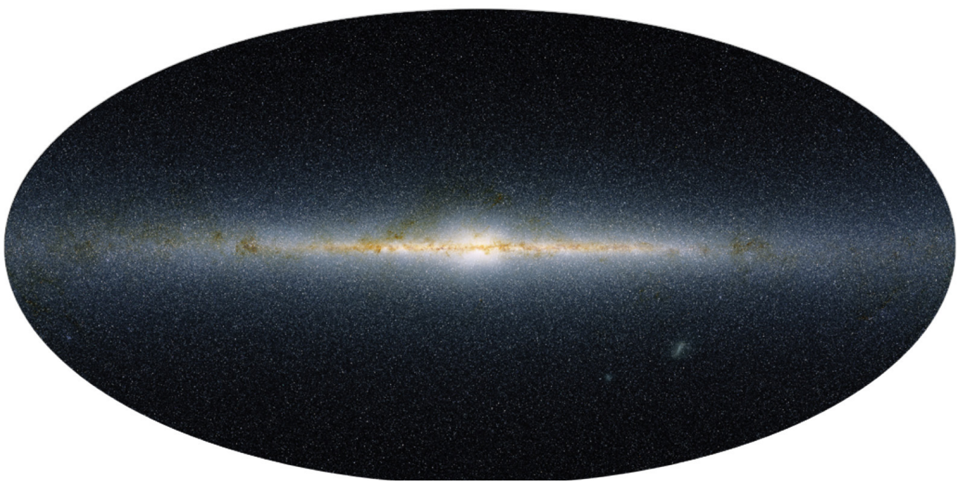


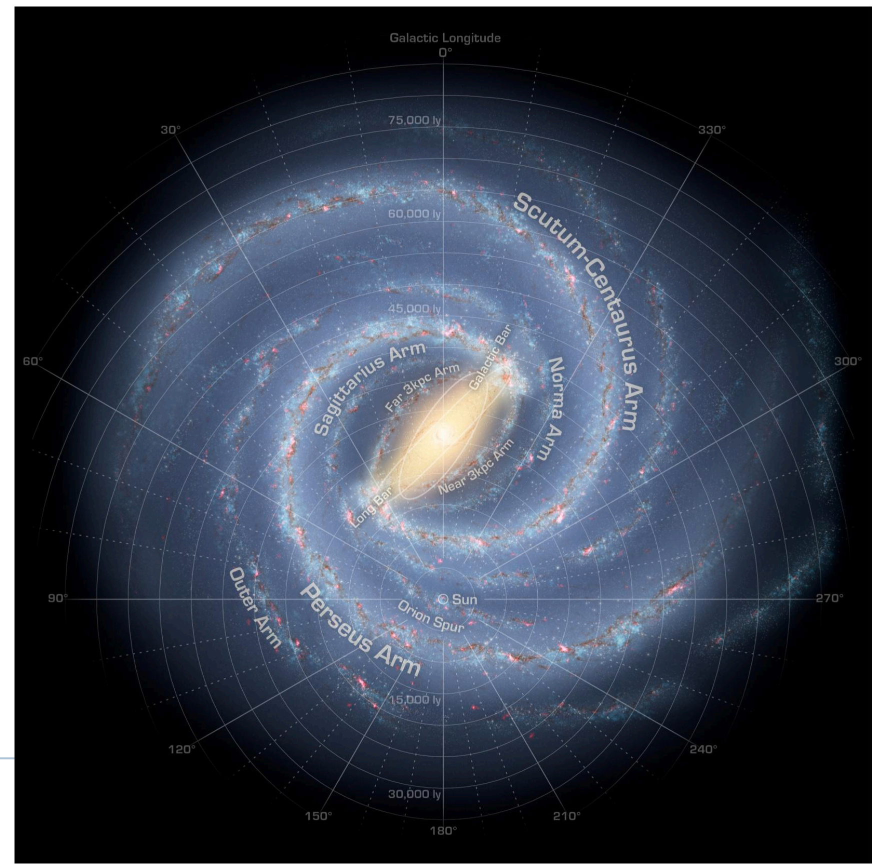




Galactic Model: disk component

- $L_{disk} = 2 \times 10^{10} L_{\odot}$ (B band)
- h_R = 3 kpc (scale length)
- z_0 = (scale height) *round numbers!*
  - = 150 pc (extreme Pop I)
  - = 350 pc (Pop I)
  - = 1 kpc (Pop II)
- R_{max} = 12 kpc
- R_{min} = 3 kpc
- Inside 3 kpc, the Galaxy is a mess, with a bar, expanding shell, etc…

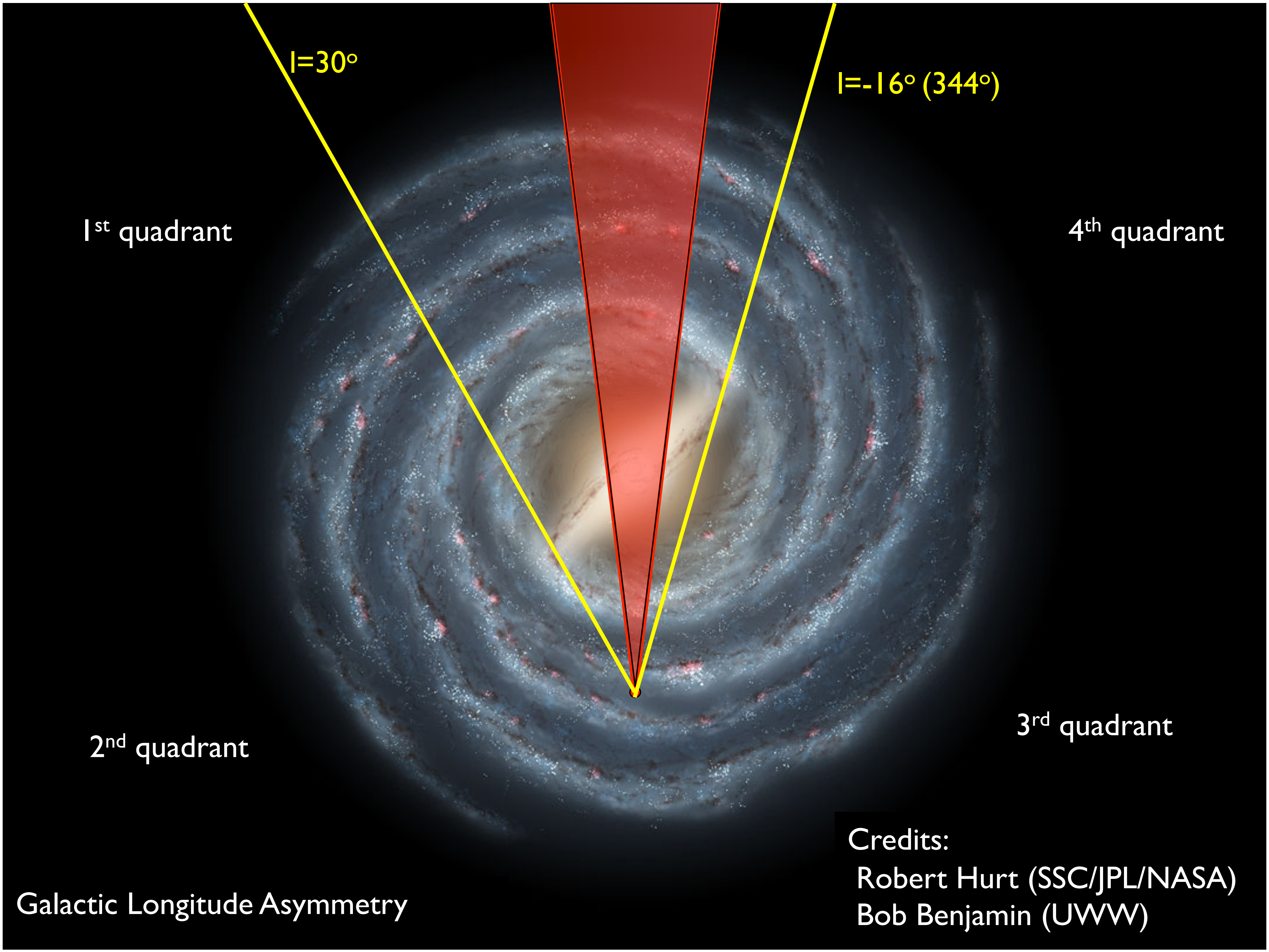




Galactic Bar

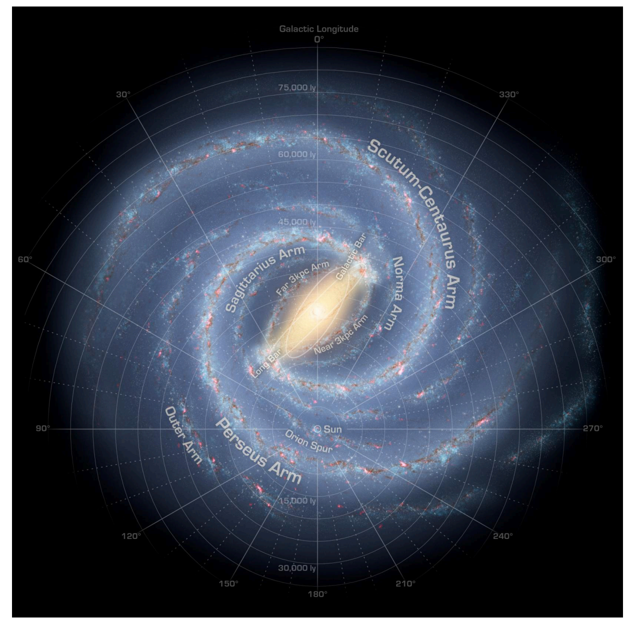
- Lots of other disk galaxies have a central bar (elongated structure). Does the Milky Way?
- Photometry – what does the stellar distribution in the center of the Galaxy look like?
  - Bar-like distribution: $N = N_0 \exp(-0.5r^2)$, where $r^2 = (x^2+y^2)/R^2 + z^2/z_0^2$
  - Observe A(m) as a function of Galactic coordinates (l,b)
  - Use N as an estimate of your source distribution:
    - counts A(m,l,b) appear bar-like
  - Sevenster (1990s) found overabundance of OH/IR stars in 1st quadrant. Asymmetry is also seen in RR Lyrae distribution.
- Gas kinematics: $V_c(r) = (4\pi G \rho /3)^{1/2} r$

  ➔ we should see a straight-line trend of $V_c(r)$ with r through the center (we don't).
- Stellar kinematics – again use a population of easily identifiable stars whose velocity you can measure (e.g. OH/IR stars).
  - Similar result to gas.


l=30°
l=-16° (344°)
1st quadrant
4th quadrant
2nd quadrant
3rd quadrant
Credits:
Robert Hurt (SSC/JPL/NASA)
Bob Benjamin (UWW)
Galactic Longitude Asymmetry

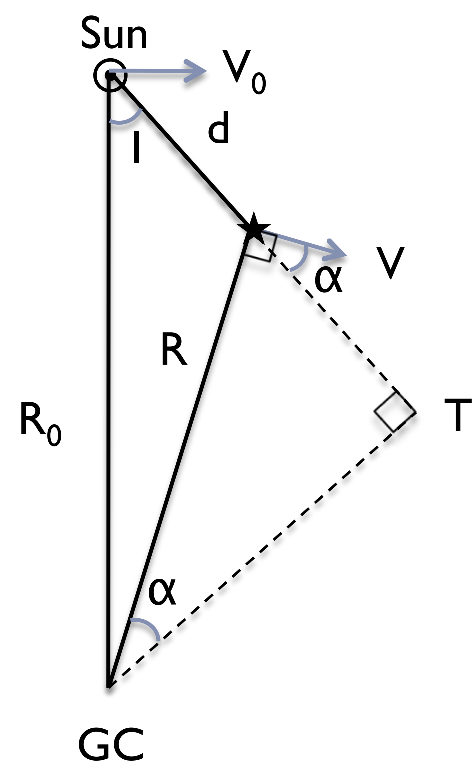
Galactic Rotation: A Simple Picture

- Imagine two stars in the Galactic disk; the Sun at distance R_0, the other at a distance R from the center and a distance, d, from the Sun. The angle between the Galactic Center (GC) and the star is l, and the angle between the motion of the stars and the vector connecting the star and the Sun is α. The Sun moves with velocity, V_0, and the other star moves with velocity, V.
  - See Figure 2.19 in S&G.



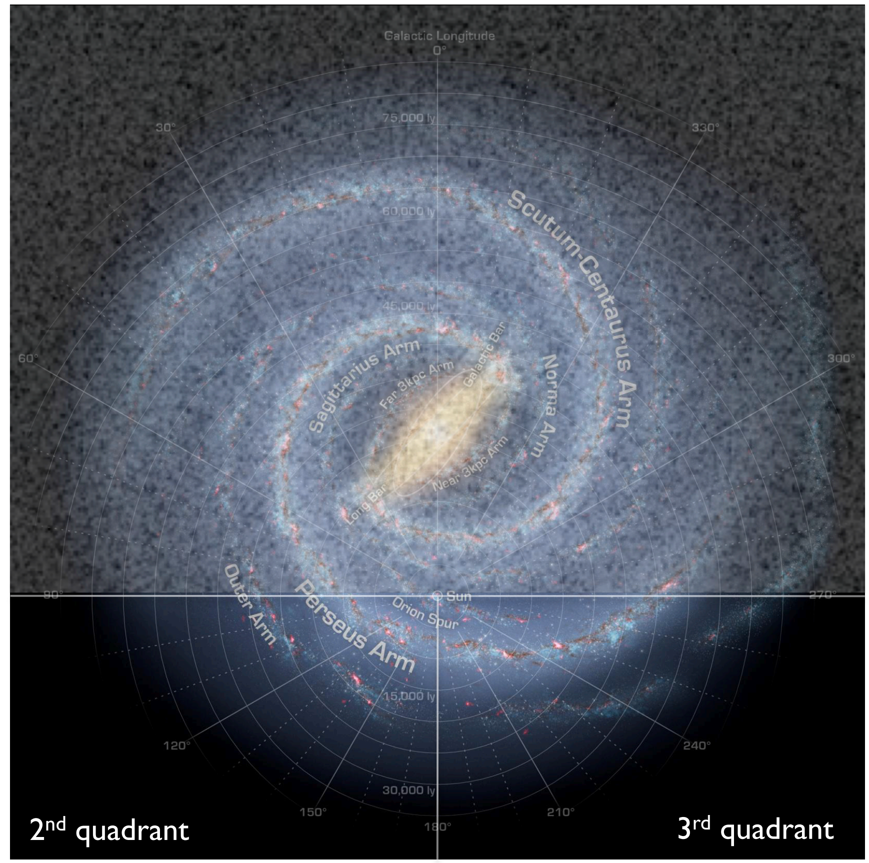
Relative motion of stars

- Radial velocity of the star
  - $V_r = V \cos\alpha - V_0 \sin l$
  - now use law of sines to get…
  - $V_r = (\omega_* - \omega_0)\, R_0 \sin l$,
    - ω is the angular velocity defined as V/R.
    - l is the Galactic longitude
- Transverse velocity of the star
  - $V_T = (\omega_* - \omega_0)\, R_0 \cos l - \omega_* d$



Longitudinal dependence

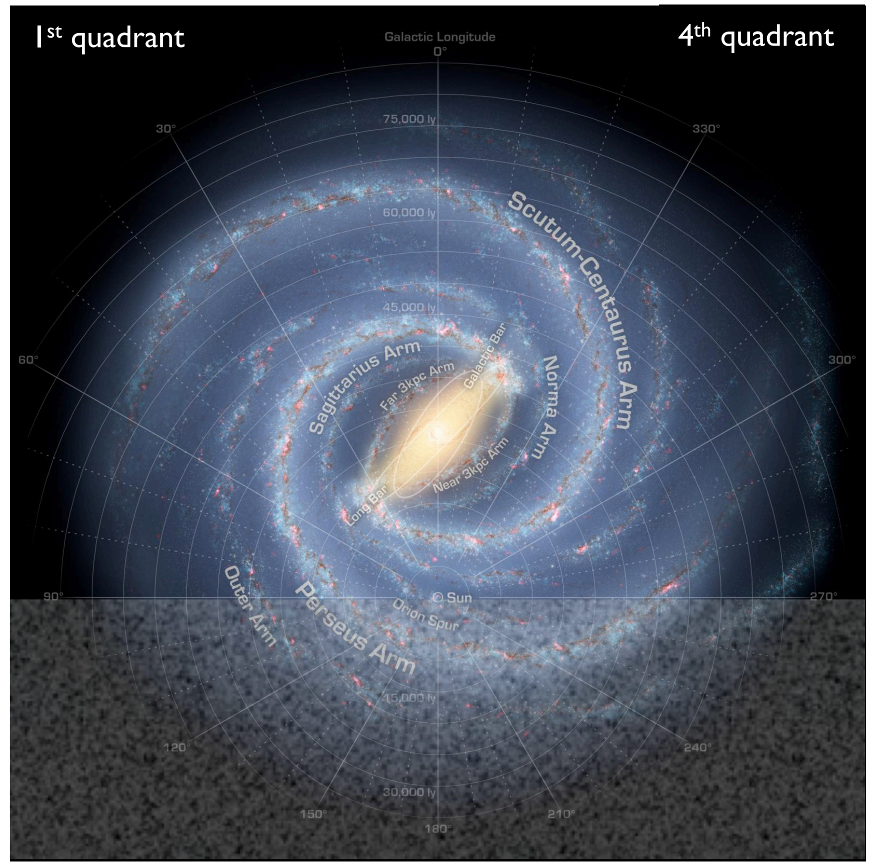
- $90^\circ \leq l \leq 180^\circ$
  - larger d
  - $R > R_0$
  - $\omega_*{}^* < \omega_0$
    - this means increasingly negative radial velocities
- $180^\circ \leq l \leq 270^\circ$
  - V_R is positive and increases with d



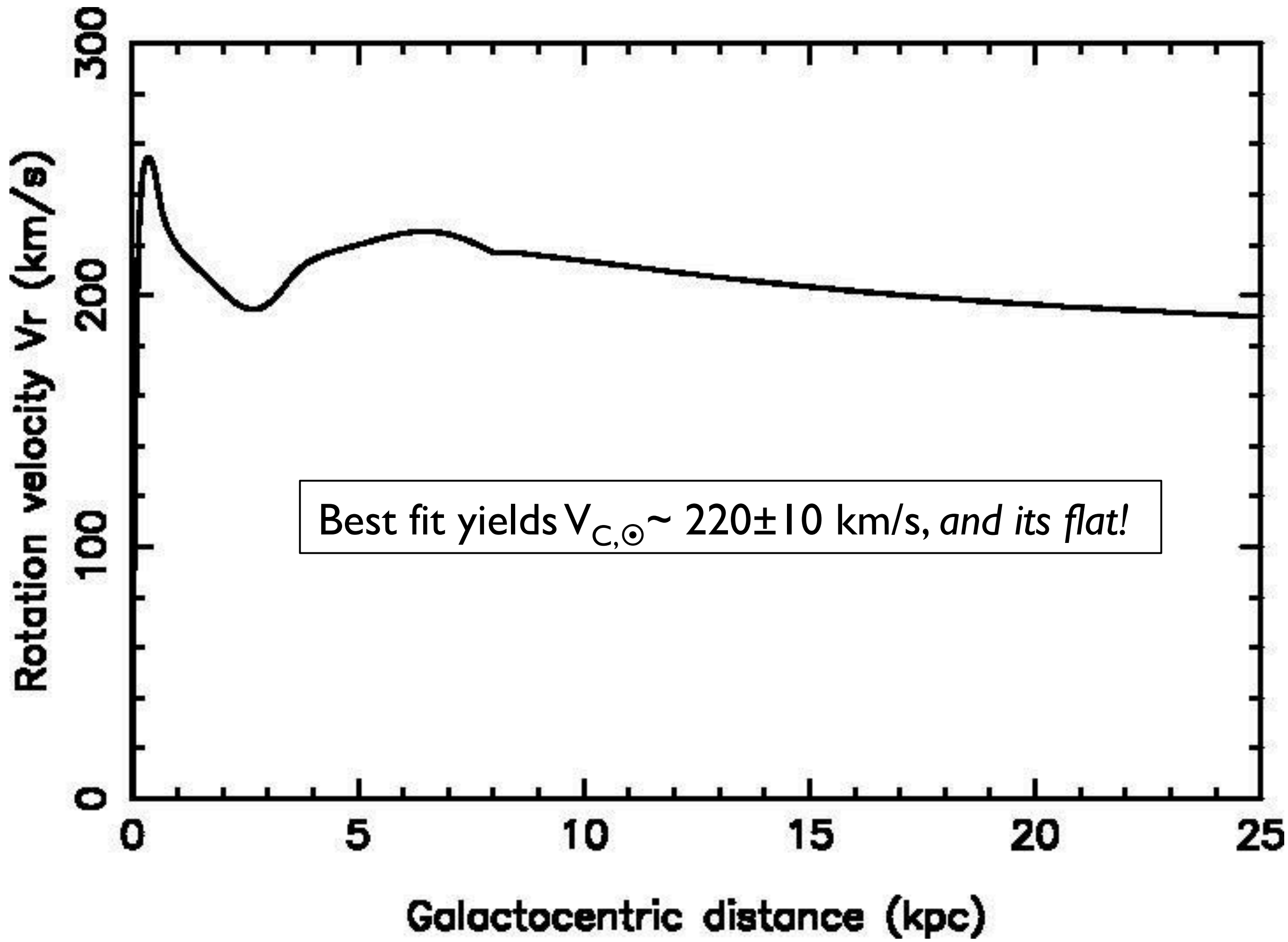
$90^\circ \leq l \leq 180^\circ$ $180^\circ \leq l \leq 270$

Longitudinal dependence

- $0° \leq l \leq 90°$
  - starting with small R, large ω
    - At some point $R = R_0 \sin(l)$ and $d = R_0 \cos(l)$
    - Here, V_R is a maximum ➔ tangent point.
    - *We can derive $\omega_*(R)$ and thus the Galactic Rotation Curve!*
- Breaks down at $l < 20°$ (why?) and $l > 75°$ (why?), but it's pretty good between 4-9 kpc from Galactic center.



Galactic Rotation Curve



Nakanishi & Sofue (2003, PASJ, 55,191)

Galactic rotation

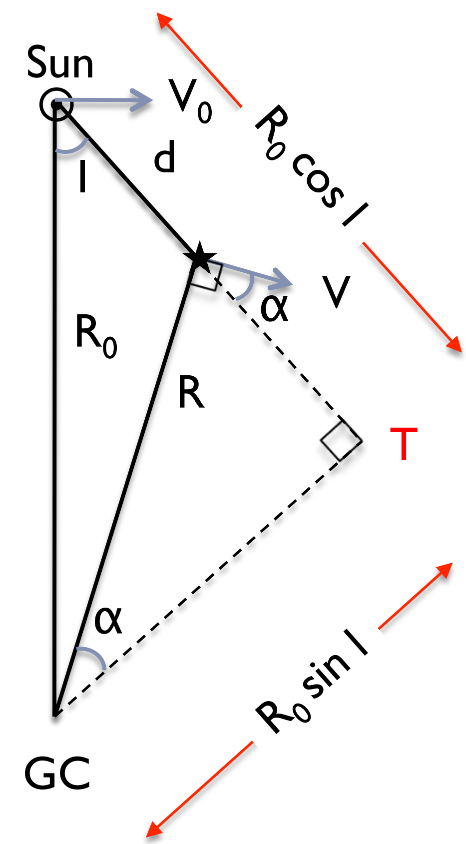
- Inner rotation curve from "tangent point" method

  ➔ $V_{circ,\odot}$= 220 km s^{-1}

  - Derived from simple geometry based on a nearby star at distance, d, from us.
  - Tangent point where R = R_0 sin l and d = R_0 cos l :

    Observed V_R is a maximum

- Outer rotation curve from Cepheids, globular clusters, HII regions ➔ anything you can get a real distance for
- Best fit: (220±10 km/s) depends on R_0 (think back to the geometry)
- Yields $\omega_0 = V_0/R_0$ = 29±1 km s^{-1} kpc^{-1}



Rotation model

- Observations of local kinematics can constrain the global form of the Galactic rotation curve
- Components of rotation model:
  - Oort's constants which constrain local rotation curve.
  - Measurement of R_0
  - Global rotation curve shape (e.g., flat)

- Oort's constants A and B:
  - $\omega_0 = V_0/R_0 = A-B$
  - $(dV/dR)_{R0} = -(A+B)$
  - $V_{c,\odot} = R_0(A-B)$

Oort's Constant A: Disk Shear

- Assume d is small
  - this is accurate enough for the solar neighborhood
- Expand $(\omega_* - \omega_0) = (d\omega/dR)_{R0}(R-R_0)$
- Do some algebra….
  - $V_R = [(dV/dR)_{R0} - (V_0/R_0)]\ (R-R_0)\ \sin l$
- If $d << R_0$,
  - $(R_0-R) \sim d \cos(l)$
  - $V_R = A\ d\ \sin(2l)$
- where $A = ½[(V_0/R_0) - (dV/dR)_{R0}]$
  - This is the 1st Oort constant, and it measures the shear (deviation from rigid rotation) in the Galactic disk.
  - In solid-body rotation A = 0
- If we know V_R and d, then we know A and $(d\omega/dR)_{R0}$

Oort's Constant B: Local Vorticity

- Do similar trick with the transverse velocity:
  - V_T= d [A cos(2l)+B], and
  - μ_l= [Acos(2l)+B]/4.74 = proper motion of nearby stars
- B is a measure of angular-momentum gradient in disk (vorticity: tendency of objects to circulate around)

Measuring Oort's Constants

- Requires measuring V_R, V_T, and d
- V_R and d are relatively easy
- V_T is hard because you need to measure proper motion
  - μ (arcsec yr^{-1}) = V_T(km s^{-1})/d (pc) = V_T/4.74d
  - Proper motions + parallaxes
- A = 14.82 km s^{-1}kpc^{-1}, B = -12.4 ± 0.6 km s^{-1} kpc^{-1}

- The interesting thing you also measure is the relative solar motion with respect to the Local Standard of Rest (LSR)

Solar Motion

- LSR ≡ velocity of something moving in a perfectly circular orbit at R_0 and always residing exactly in the mid-plane (z=0).
- Define cylindrical coordinate system:
  - R (radial)
  - z (perpendicular to plane)
  - ϕ (azimuthal)
- *Residual* motion from the LSR:
  - u = radial, v = azimuthal, w = perpendicular
- *Observed* velocity of star *w.r.t. Sun*:
  - $U_* = u_* - u_\odot$, etc. for v, w
- Define means:
  - $\langle u_* \rangle = (1/N) \Sigma u_*$, summing over i=1 to N stars, etc. for v,w
  - $\langle U_* \rangle = (1/N) \Sigma U_*$, etc for V,W

Solar Motion

- Assumptions you can make
  - Overall stellar density isn't changing
    - there is no net flow in either u (radial) or w (perpendicular):
    - $\langle u_* \rangle = \langle w_* \rangle = 0$.
  - If you do detect a non-zero $\langle U_* \rangle$ or $\langle W_* \rangle$, this is the reflection of the Sun's motion:
  - $u_\odot = -\langle U_* \rangle$, $w_\odot = -\langle W_* \rangle$, $v_\odot = -\langle V_* \rangle + \langle v_* \rangle$

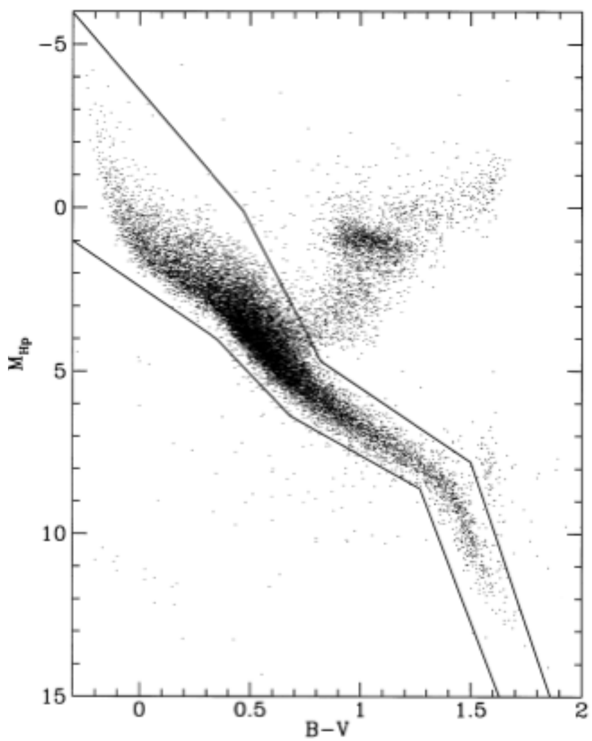
- Dehnen & Binney 1998 MNRAS 298 387 (DB88)
  - Parallaxes, proper motions, etc for solar neighborhood (disk pop only)
  - $u_\odot = -10.00 \pm 0.36$ km s^{-1} (inward; DB88 call this U_0)
  - $v_\odot = 5.25 \pm 0.62$ km s^{-1} (in the direction of rotation; DB88 call V_0)
  - $w_\odot = 7.17 \pm 0.38$ km s^{-1} (upward; DB88 call this W_0)
  - No color dependency for u and w, but for v….

Solar Motion

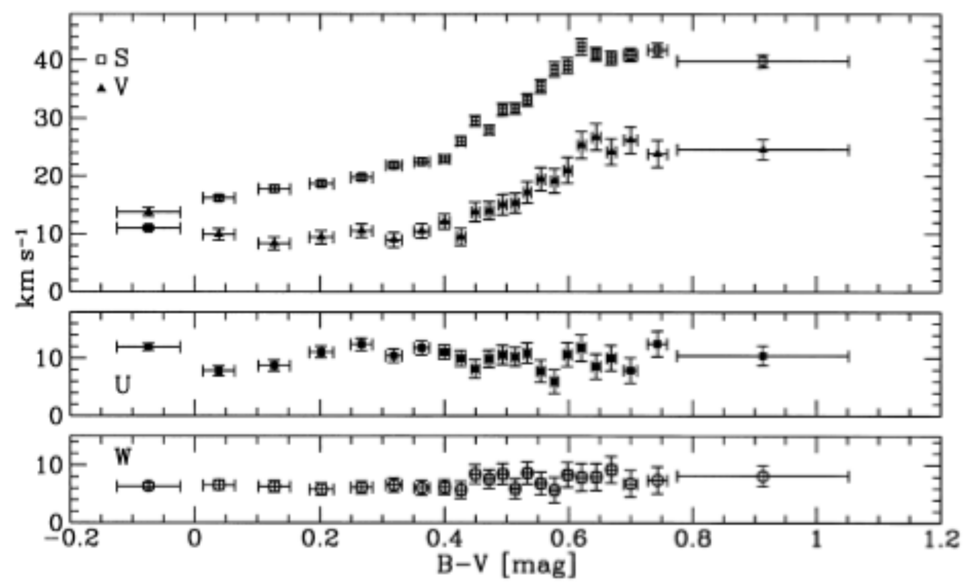
- Leading & Lagging
  - Stars on perfectly circular orbits with $R=R_0$ will have $\langle V \rangle = 0$.
  - Stars on elliptical orbits with $R>R_0$ will have higher than expected velocities at R_0 and will "lead" the Sun
  - Stars on elliptical orbits with $R<R_0$ will have lower than expected velocities at R_0 and will "lag" the Sun
- Clear variation in $v_\odot$ with (B-V)!
  - Why?
  - Why only v and not u or w?
- We can also measure the random velocity, S^2, and relate this to $v_\odot$. This correlation is actually predicted by theory (as we shall see)!
  - $S = [\langle u^2 \rangle + \langle v^2 \rangle + \langle w^2 \rangle]^{1/2}$

Parenago's Discontinuity

Clues to disk evolution:



Hipparcos catalogue:
geometric parallax and
proper motions



τ_{ms} ➔ mean age

Binney et al. (2000, MNRAS, 318, 658)

$S = S_0\,[1+(t/\mathrm{Gyr})^{0.33}]$ ← random grav. encounters

$S_0 = 8$ km s^{-1} ← why might this be?

See also Wielen 1977, A&A, 60, 263

Solar Motion

- Stellar motion in the disk is basically circular with some modest variations.
- There is an increase in the velocity dispersion of disk stars with color ➔ age
  - Seen in vertical, radial, and azimuthal dimensions
  - Results in $v_{\odot}$ correlation with (B-V)
  - What about the thickness of the disk?
- Disk stars come in all different ages, but tend to be metal rich…

The Halo: Clues to formation scenario?

- Layden 1995 AJ 110 2288
  - Age of halo RR Lyrae stars > 10 Gyr
  - $-2.0 < [Fe/H] < -1.5$; $V_{rot}/\sigma_{los} \sim 0$; $\sigma_{los} \sim 100\text{-}200$ km s^{-1}
  - $-1.0 < [Fe/H] < 0$; $V_{rot}/\sigma_{los} \sim 4$; $\sigma_{los} \sim 50$ km s^{-1}
- Relative to LSR
  - $\langle U \rangle = -13$ km s^{-1}
  - $\langle W \rangle = -5$ km s^{-1}
  - $\langle V \rangle_{[Fe/H]<-1.0} = 40$ km s^{-1}
  - $\langle V \rangle_{[Fe/H]>-1.0} = 200$ km s^{-1}

Velocity dispersion defined:

$$\sigma^2_{los} = \int (v_{los} - \underline{v})^2 F(v_{los})\, dv_{los}$$

or, $\sigma_{los} = ((v - \underline{v})2)^{1/2}$

where $F(v_{los})$ = velocity distribution function

- Conclusion: there is an extended old, metal poor stellar halo dominated by random motions with very little, if any, net rotation ($0 < V < 50$ km/s)

Globular Cluster Population

- Harris, W.E. 2001 "Star Clusters"
  - ~150 globular clusters in MWG
  - Distribution is spherically symmetric, density falls off as $R_{GC}^{-3.5}$
  - Bimodal metallicity distribution
    - [Fe/H] ~ -1.7 (metal-poor) ➔ found in halo
    - [Fe/H] ~ -0.2 (metal rich) ➔ found in bulge

Measuring Galactic Rotation: Example

- Select stars of a single spectral type….A stars

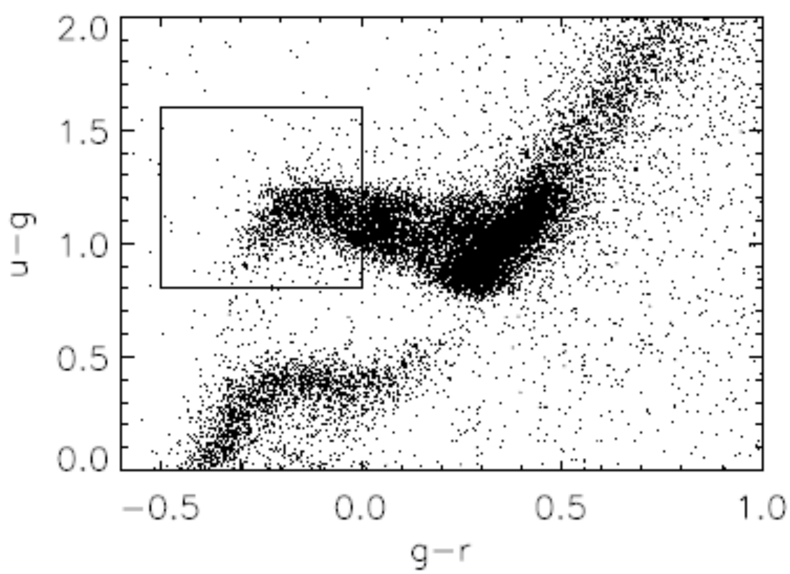
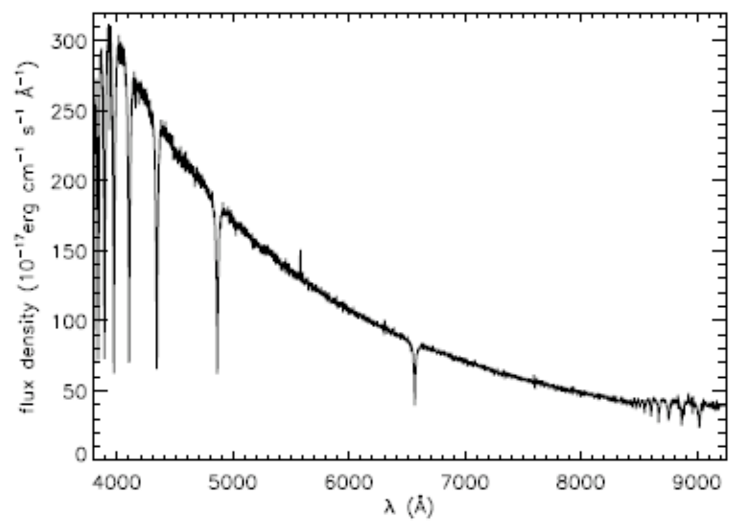


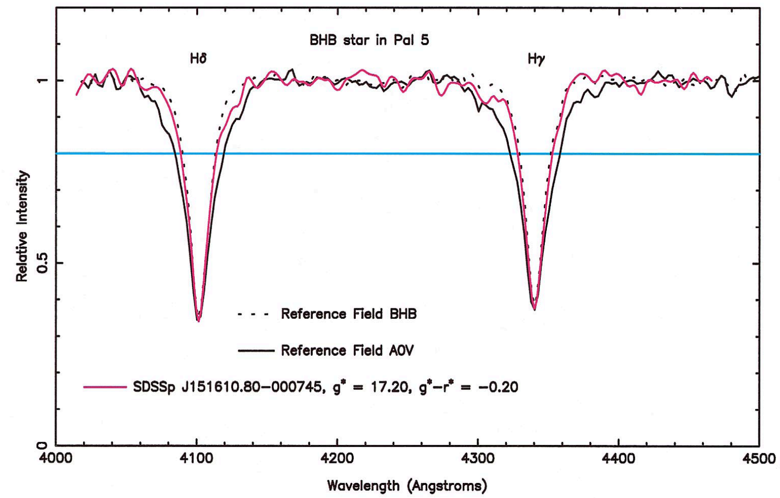
FIG. 1.—SDSS color-color diagram showing all spectroscopically targeted objects that were subsequently confirmed as stars. The large Balmer jump of A-type stars places them in the region where our "color-cut" selection box is drawn. This color selection approach follows Yanny et al. (2000).

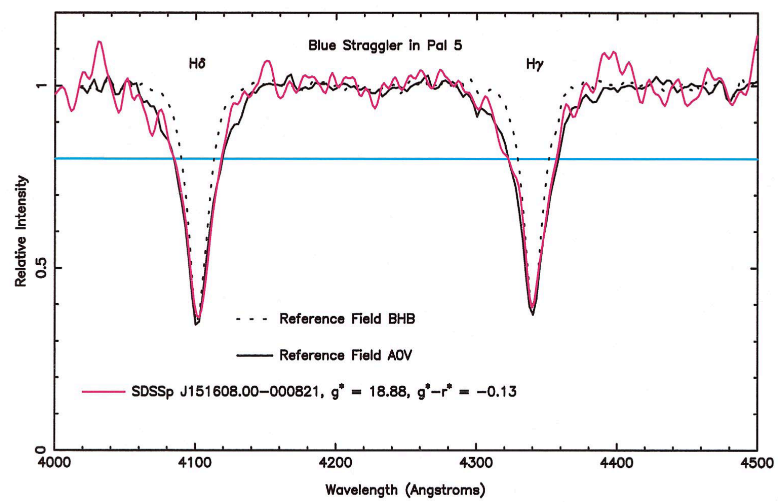


Xue et al. 2008

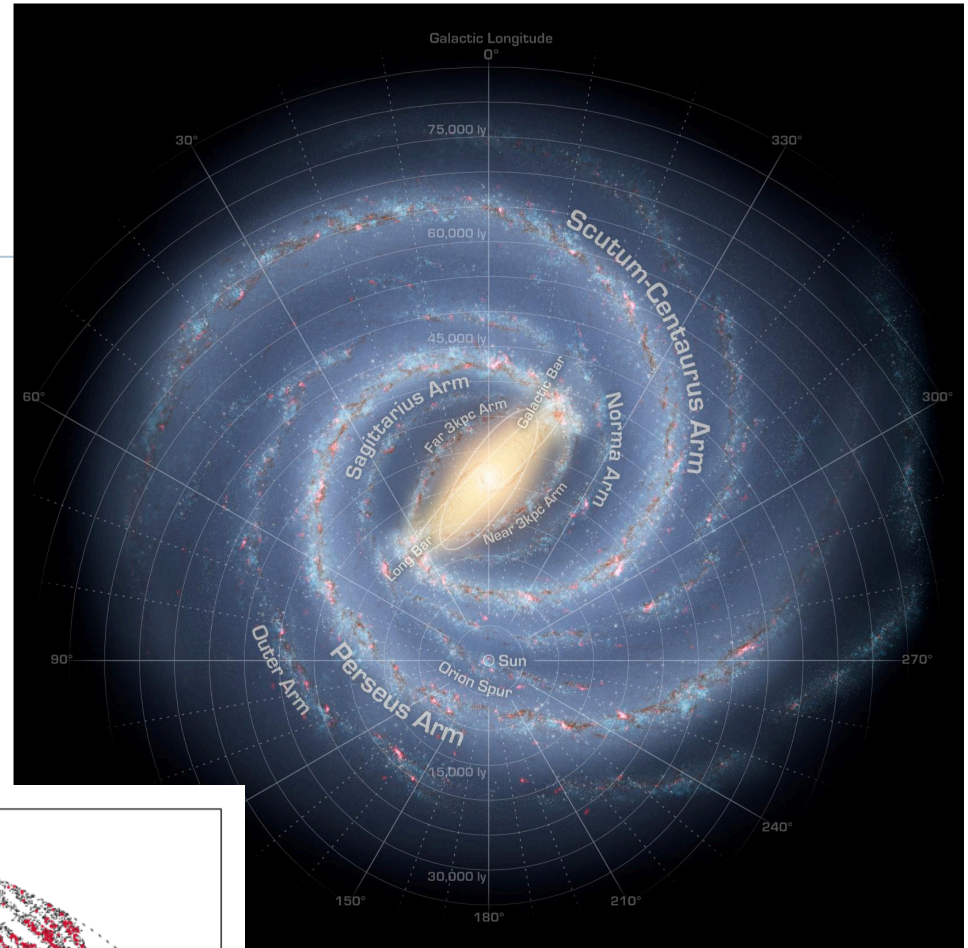
Measuring Galactic Rotation: Example

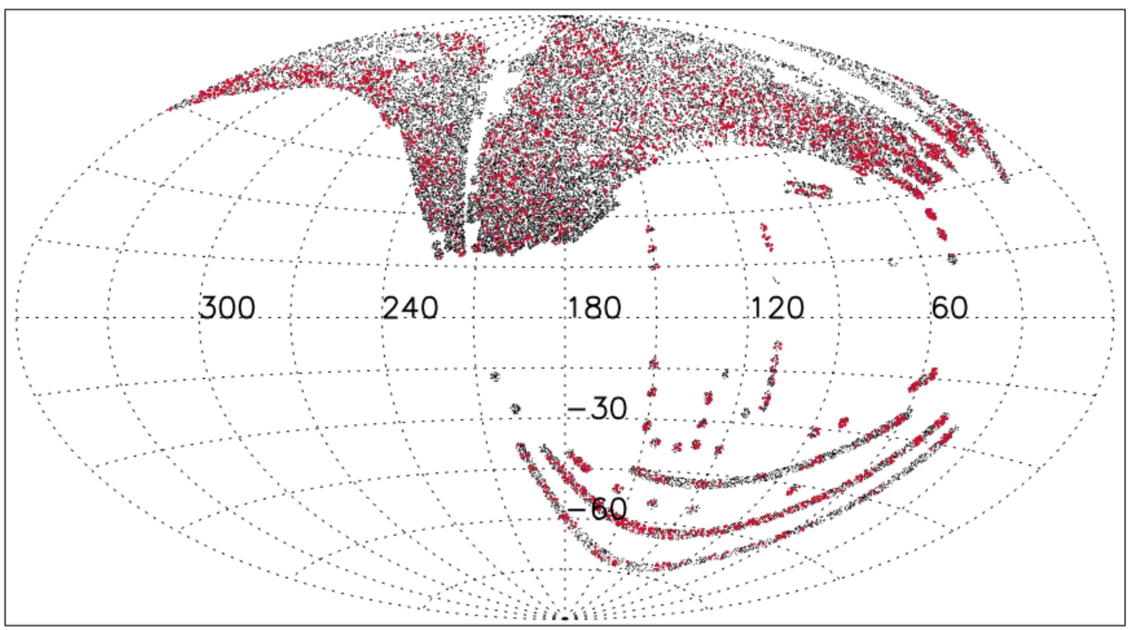
- Distinguish between blue horizontal branch stars and blue stragglers (MS) so the luminosity is known
- Infer distances





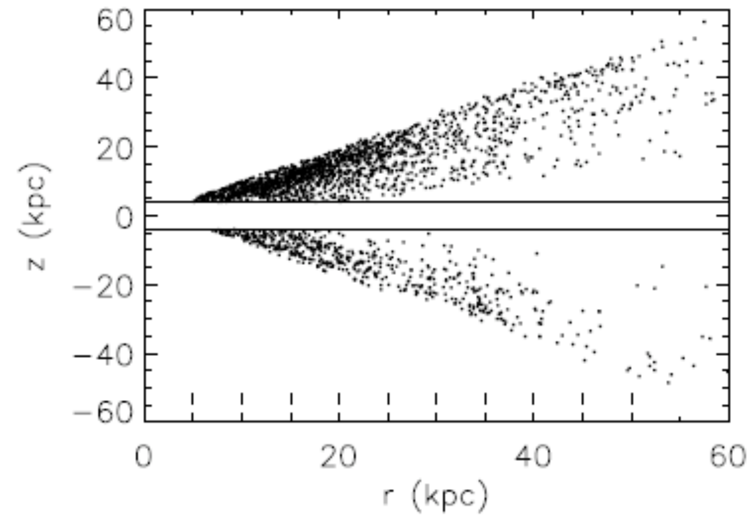
Sight Lines

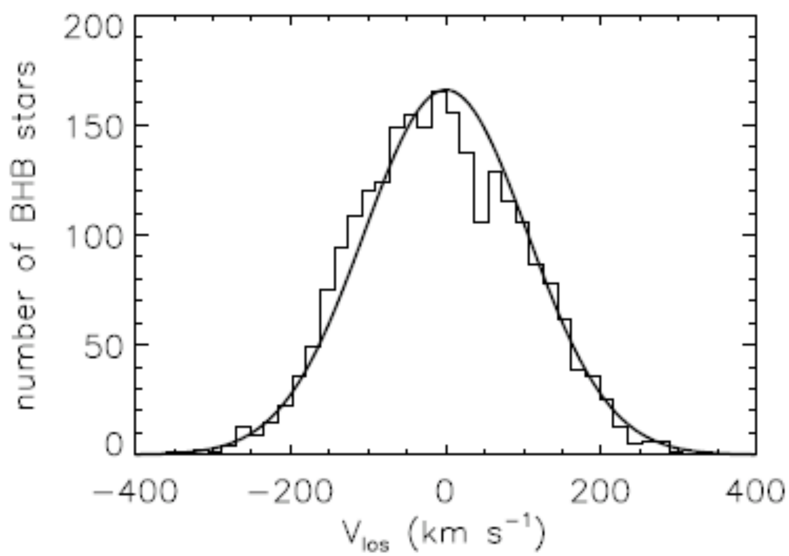

Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Orion Spur
Sun

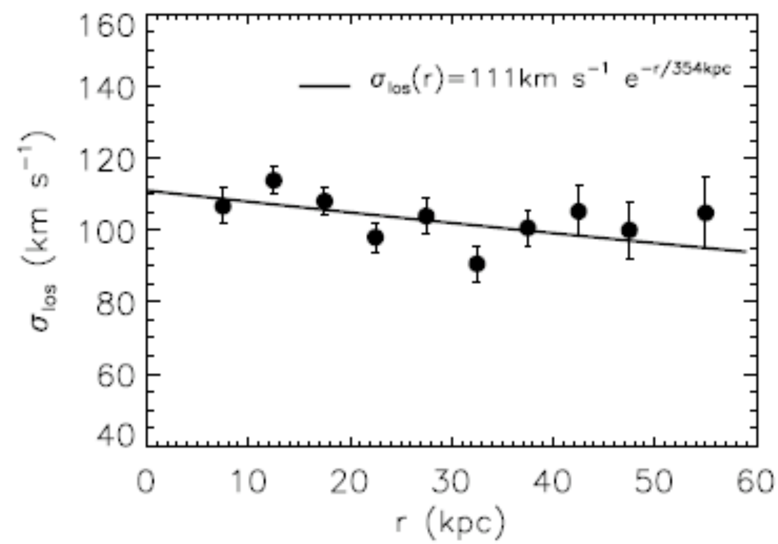

300
240
180
120
60
−30
−60

Measuring Galactic Rotation: Example

- Determine the spatial distribution w.r.t. the GC ➔
- Measure the observed distribution of line-of-sight velocities (🡇 V_{los}), and the dispersion of these velocities, σ_{los}, as a function of Galactic radius ➘







Measuring Galactic Rotation: Example

- And now the trick: Estimate circular velocity (the rotation curve) from the velocity-dispersion data.

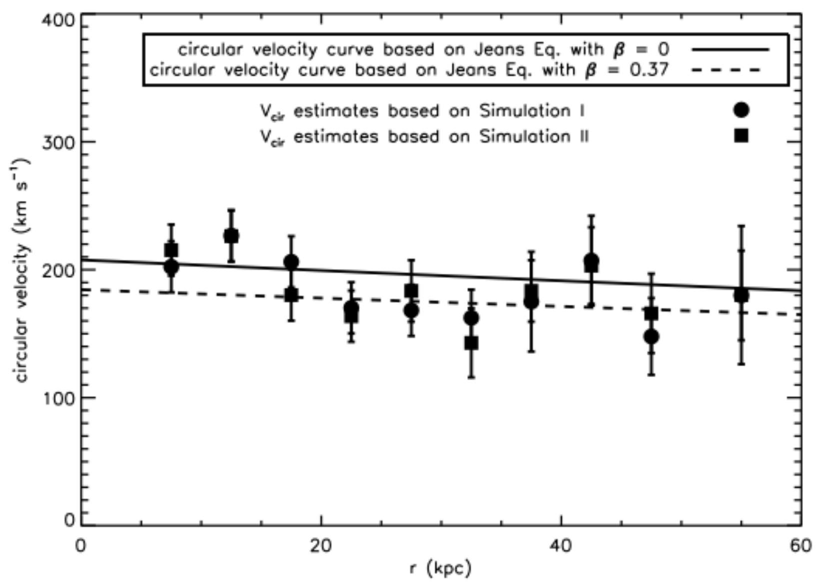


FIG. 15.—Distribution of circular velocity estimates, $V_{\rm cir}$, for two different simulated galaxies. The circles represent the $V_{\rm cir}$ estimates for the observed halo BHB stars based on simulation I, and the squares represent the $V_{\rm cir}$ estimates based on simulation II. The two lines show the circular velocity curve estimates derived from the velocity dispersion profile (Fig. 10) and the Jeans equation with $\beta = 0.37$ and $\beta = 0$.

For reference, we show how these estimates of $V_{\rm cir}(r)$ compare to those derived from the Jeans equation and the fit to $\sigma_{\rm los}(r)$ shown in Figure 10. From the Jeans equation, $V_{\rm cir}(r)$ can be estimated from the velocity dispersion, σ_r (Binney & Tremaine 1987), as follows:

$$-\frac{r}{\rho}\frac{d(\sigma_r^2\rho)}{dr} - 2\beta\sigma_r^2 = V_{\rm cir}^2(r), \quad (8)$$

with

$$\beta = 1 - \frac{\sigma_t^2}{\sigma_r^2}, \quad (9)$$

where $\sigma_r(r)$ and $\sigma_t(r)$ are the radial and tangential velocity dispersions, respectively, in spherical coordinates and $\rho(r)$ is the stellar density.

- So we need to learn some dynamics

Why Dynamics?

- We can then also interpret the data in terms of a physical model:

Mass decomposition of the rotation curve into bulge, disk and halo components :
➔ Dark Matter
➔ Stellar M/L ≡ Υ_*
➔ The IMF
➔ Missing physics