Astronomy 730

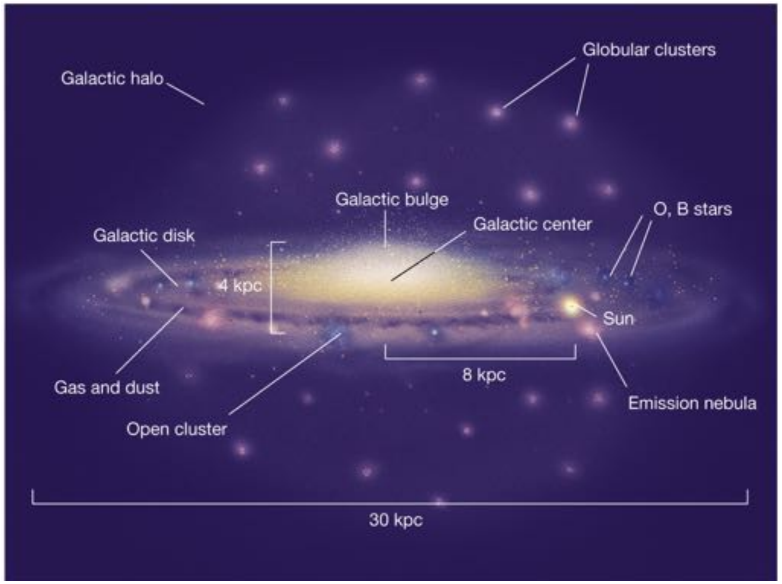
Milky Way

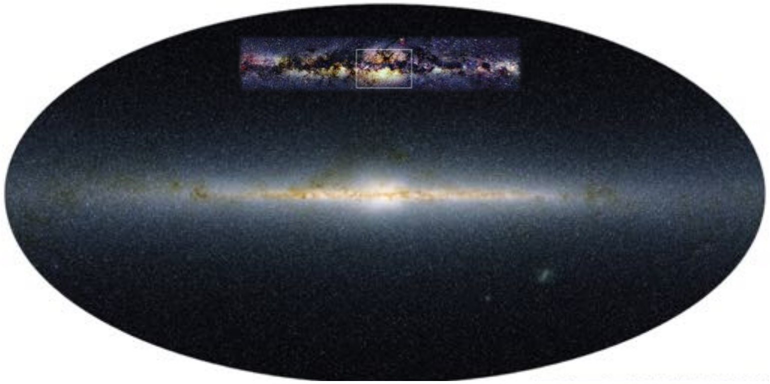
Outline

- The Milky Way
  - Star counts and stellar populations
    - Chemical cartography
  - Galactic center and bar
  - Galactic rotation
    - Departures from circular rotation

Modeling the Milky Way Galaxy (MWG)

- What is the stellar distribution?
- How big is the Milky Way?
  - Does (where does) the disk have an outer truncation?
- Does it have a bar?
- How do the stars move in the galaxy?
  - Galactic rotation and Oort's constants



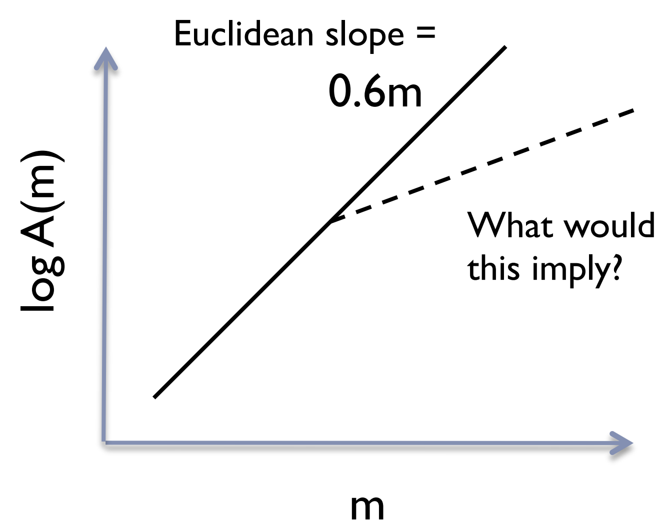


Star Counts

- Formalism
  - $N(M,S)=\int \Phi(M,S)D(r)r^2dr$
    - N = # of field stars of a given absolute magnitude (M) and spectral type (S) in the galaxy
    - Φ = stellar luminosity function (# pc^{-3} for some spectral type)
    - D(r) = density distribution
      - may also depend on M,S: D(r,M,S)
      - Alternatively, Φ may also depend on r
- The simplest thing we can actually observe:
  - A(m) = # of stars of some apparent magnitude, m.
  - $A(m) = \int \Phi(M)\, D(r)\, \Omega\, r^2\, dr$
    - Ω = solid angle of survey
- If we have colors, we might get a crude A(m,S)
  - but without distances or some luminosity indicator, we can't break the dwarf-giant degeneracy (e.g., K V vs K III).

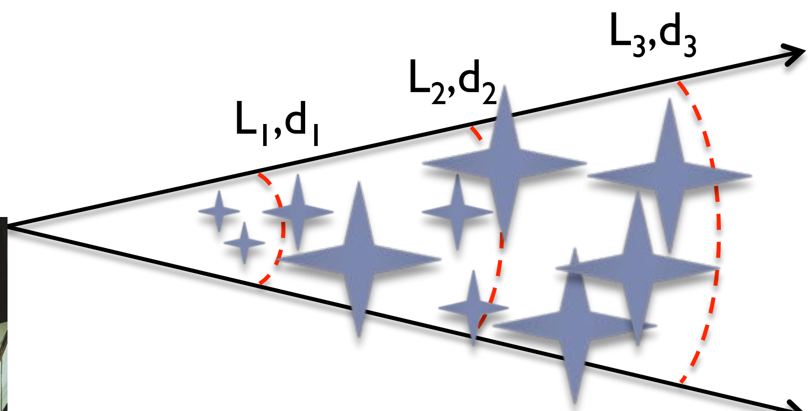
Star Counts: Infinite Euclidean Universe

- A(m) represents the differential counts, i.e., number of stars per apparent magnitude interval
- Knowing the geometry (locally Euclidean), the count slope (dA/dm) tells us about the spatial distribution of sources.
- For a *uniform* space-distribution of sources it is straightfoward to show
  - $d(\log A)/dm = 0.6m + \text{constant}$
- This leads to Olbers' paradox:
  - $l(m) = l_0 d\exp(-0.4m)$
  - $L(m) = l(m)A(m)$
  - $L_{tot} = \int l(m)A(m)\, dm = \infty$
- The distribution of stars in the galaxy must be spatially finite
- *What about the universe of galaxies?*



The Malmquist Bias & the Night Sky

- What stars do you see when you look up at the night-time sky?
- Does this make sense given what you know about the HR diagram
- Malmquist bias:
  - You can see brighter objects farther away to a fixed m
  - Volume increases as d^3



For a uniform space-density, the observer is biased toward finding intrinsically luminous objects.

The Malmquist Bias & the Night Sky

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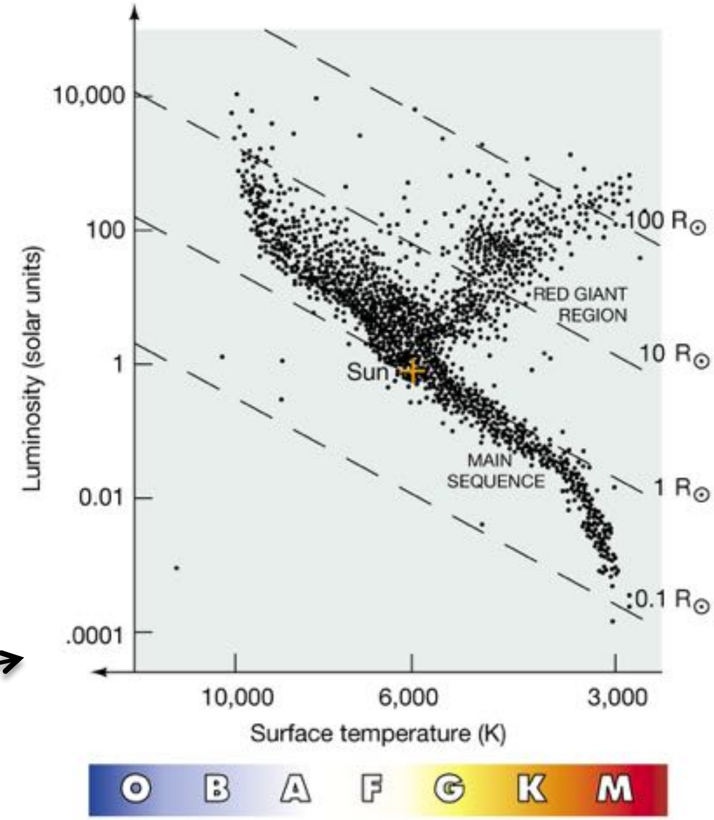
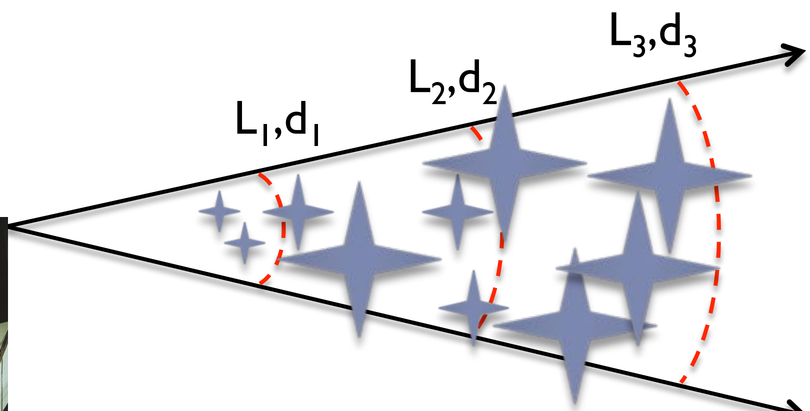
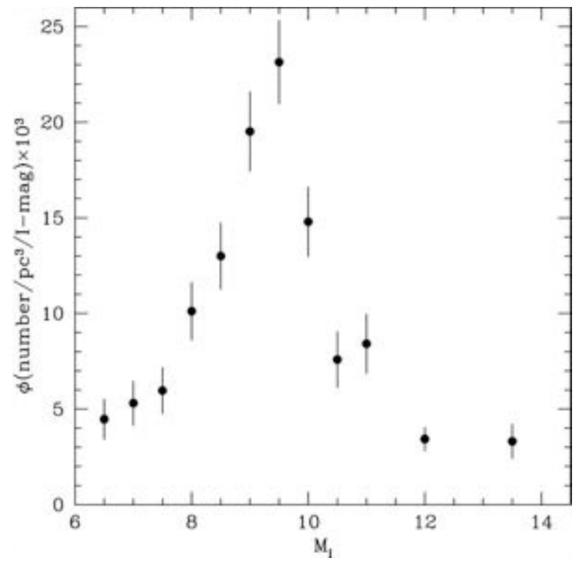




For a uniform space-density, the observer is biased toward finding intrinsically luminous objects.

Star Counts & The Malmquist Bias

- What's the mean magnitude of stars with apparent magnitude, m?
  - $M(m) = \int M\Phi(M)D(r)r^2dr / \int\Phi(M)D(r)r^2dr$
  - Recall $A(m) = \int \Phi(M) D(r)\Omega r^2dr$
- Assume the stellar luminosity function (LF) is Gaussian for a given spectral type:
  - $\Phi(M,S) = \Phi_0/(2\pi)^{1/2}\sigma \exp[-(M-M_0)^2/2\sigma^2]$
  - M_0= mean magnitude
  - Φ_0= # pc^{-3} for some spectral type
  - σ is the distribution width



Zheng et al. (2004, ApJ, 601 500): MW disk M-dwarfs, *I*-band, *HST*

Star Counts & The Malmquist Bias

- Push through the integral for M(m) and move things around a bit….
  - $M(m) = M_0 - [\sigma^2/A(m,S)]\ [dA(m,S)/dm]$
  - Or:

$$M(m) - M_0 = -\sigma^2\, d\ \ln A / dm$$

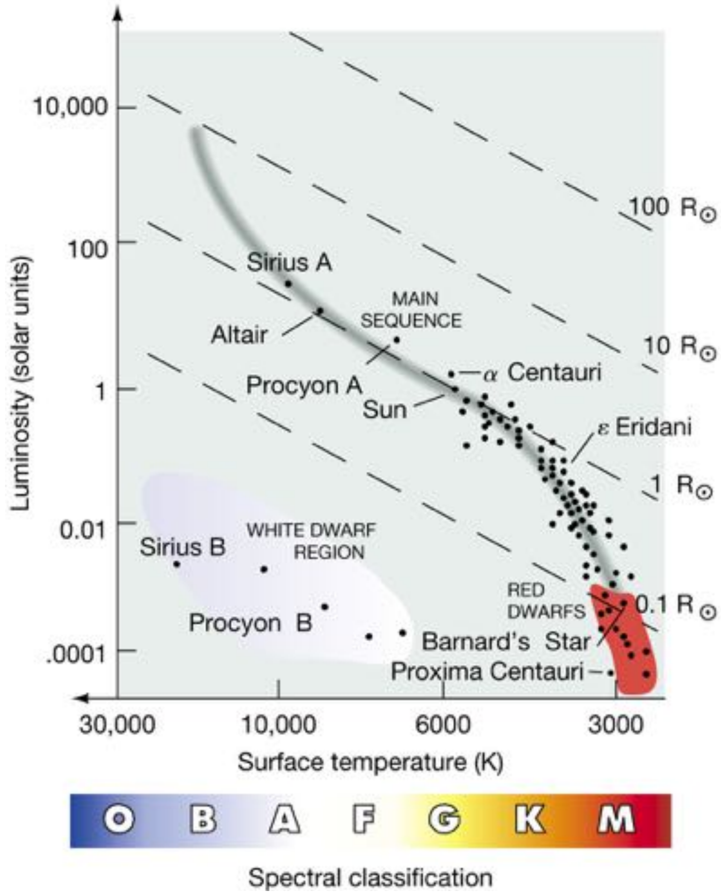
This is for the specific case of a Gaussian LF, but it can be generalized.

- If there are more stars at faint magnitudes, then the stars at some m are more luminous than the average for all stars in a given volume
  - This will come back to bite us with a vengeance when considering distant galaxy counts

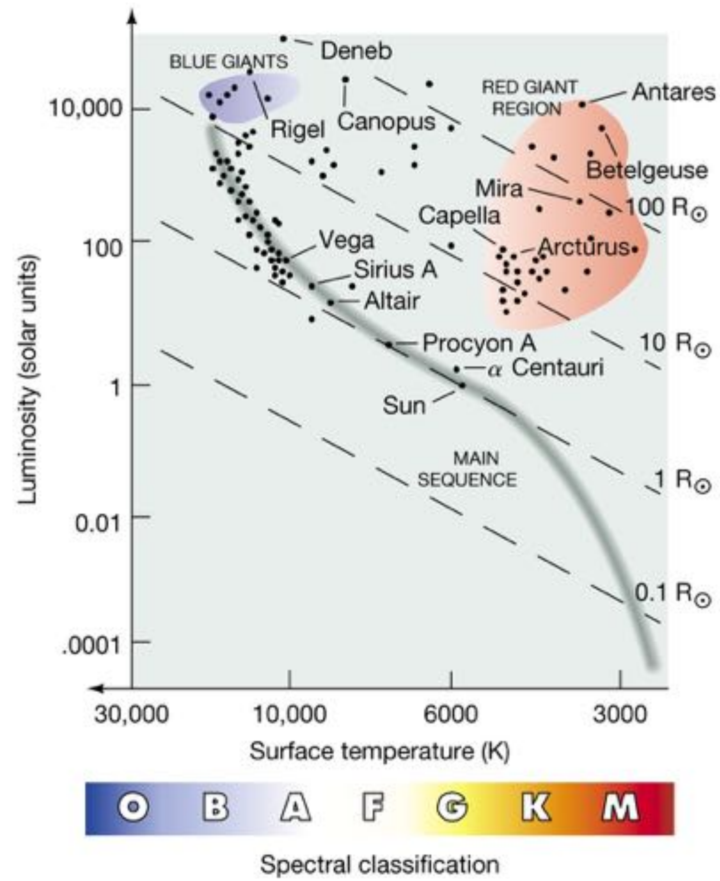
A note on logarithmic derivatives:
$d \ln x = dx / x$
This is nice because it normalizes the gradient to the amplitude of the signal, i.e., dimensionless.
Therefore often used in Astronomy

Space Densities: Local Neighborhood

Volume-limited



Brightness-limited

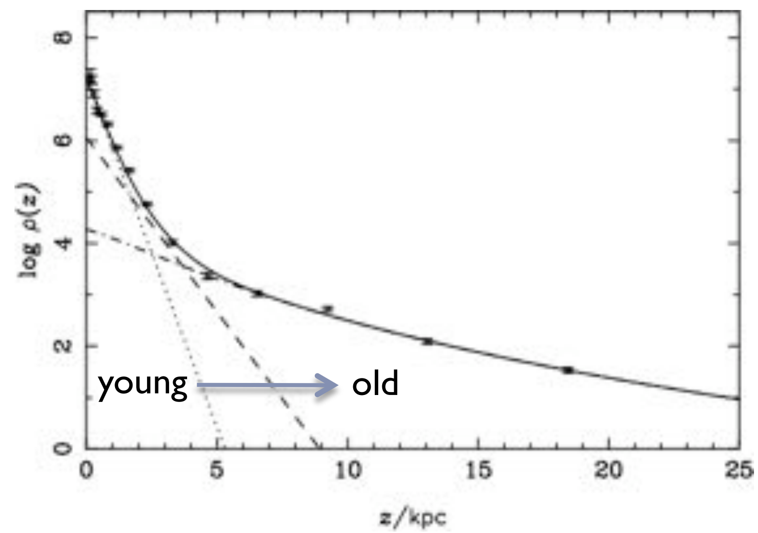


Stellar Luminosity Function

- Measure for a distance(volume)-limited sample
- Bahcall & Soneira (1980) used:
  - $\Phi(M) = [n_* 10^{\beta(M-M_*)}] / [1+10^{-(\alpha-\beta)\delta(M-M_*)}]^{1/\delta}$
    - $n_* = 4.03 \times 10^{-3}$
    - $M_* = 1.28$
    - $\alpha = 0.74$, $\beta = 0.04$, $1/\delta = 3.40$
- See also Figure 2.4 in S&G.
- Basic results
  - 10^5 times more G stars than O stars
  - Nearby stars tend to be
    - low-luminosity and apparently faint
  - Average $M/L = 0.67\ (M/L)_\odot$

Star Counts: The Disk

- Star counts (z direction)
  - n(z) proportional to $\exp(-z/z_0(m))$,
    - $z_0(m)$ is the scale height (and, yes, it does vary with magnitude)
  - More importantly, z_0 varies with spectral type:
    - young : old ➔ small : large
    - **WHY?**
  - Reid & Majewski (1993)
    - Thin disk with z_0= 325 pc – Pop I
    - Thick disk with z_0= 1200 pc – Pop II
- The Disk
  - $I(R) = I(0)\exp[-R/h_R]$
  - tough to measure in our own galaxy, but measurable in other disks pretty easily.
- Disk is really a double exponential:
  - $I(R,z) = I(0,0)\exp(-z/z_0-R/h_R)$



Du et al. 2003 A&A 407 541, stellar density perpendicular to the plane

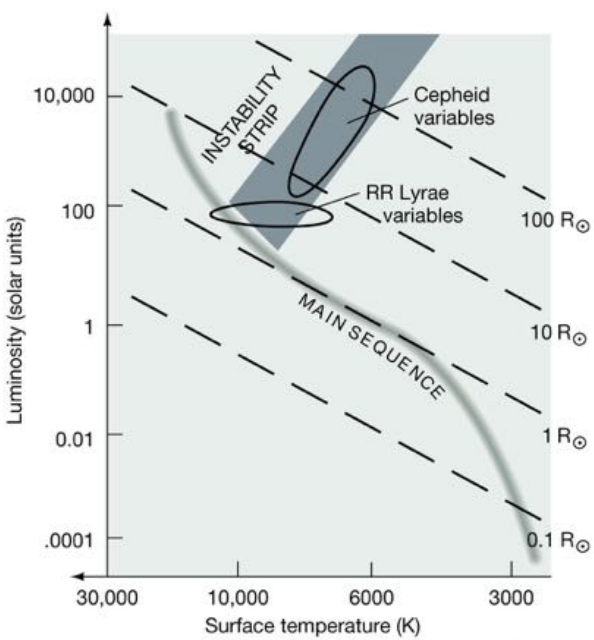
Star Counts: The Halo

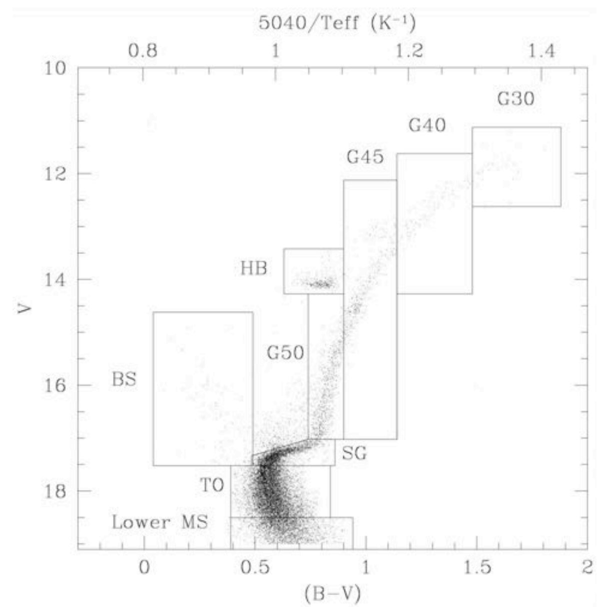
- Halo stars
  - Halo stars are faint, need an easy to find tracer

    RR Lyrae stars
  - Stellar density falls off as r^{-3}
  - Looks like the distribution of globular clusters, which you also get from RR Lyrae stars
- We will come back to this density fall-off when we consider the rotation curve.

Recall: RR Lyrae Stars

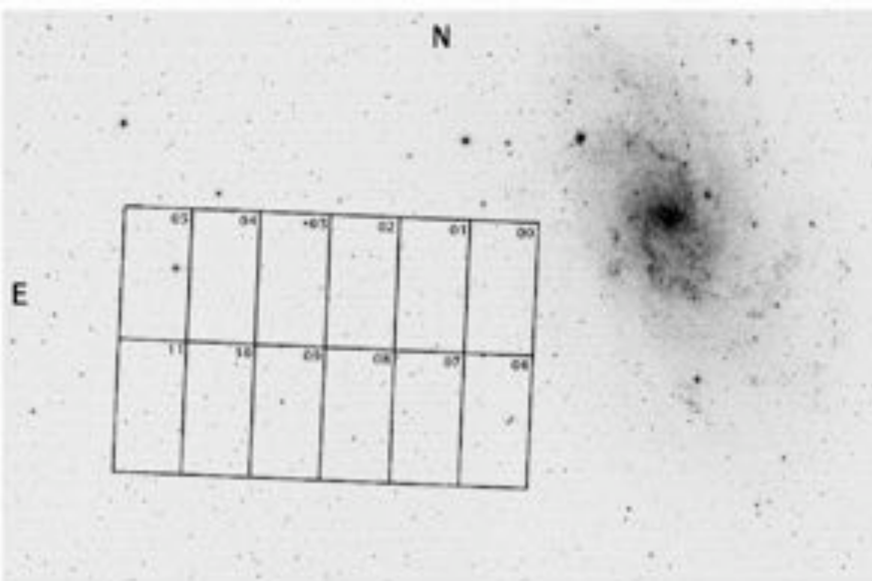
- HB stars in "the instability strip"
  - Solar mass
  - Opacity driven pulsations yield variability which is correlated with M
  - M = -2.3±0.2 log(P) –0.88±0.06 (with some additional variation due to metallicity)
  - Old, low mass stars (hence good tracers of the halo)
- Higher mass (farther up the instability strip you'll find Cepheids)

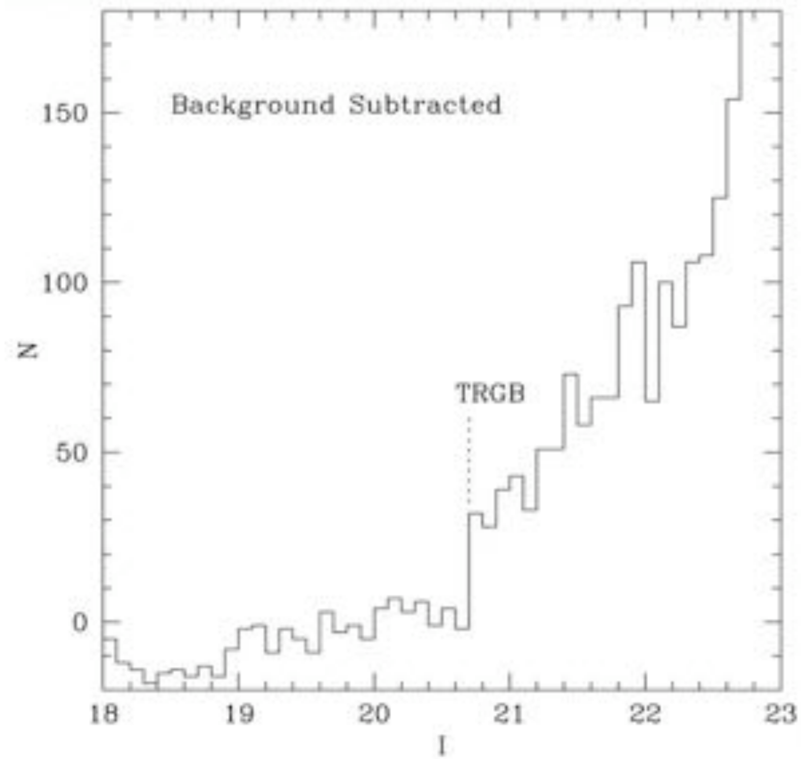




M33 LF

- Outer fields of M33
  - (Brooks et al. 2004, AJ, 128, 237)



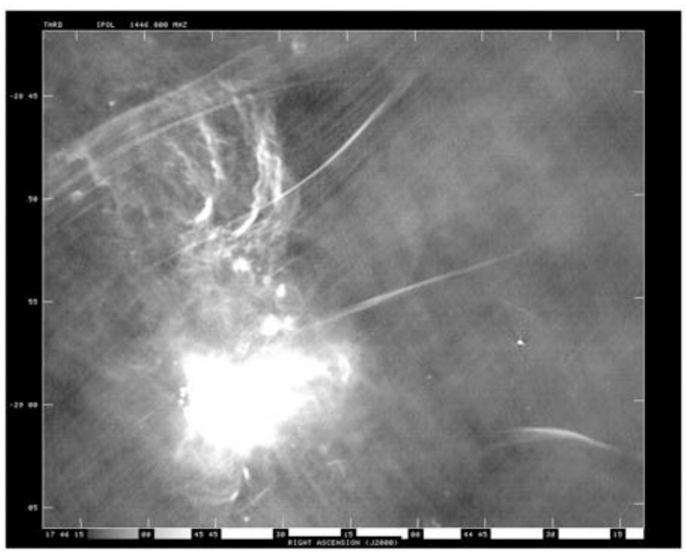


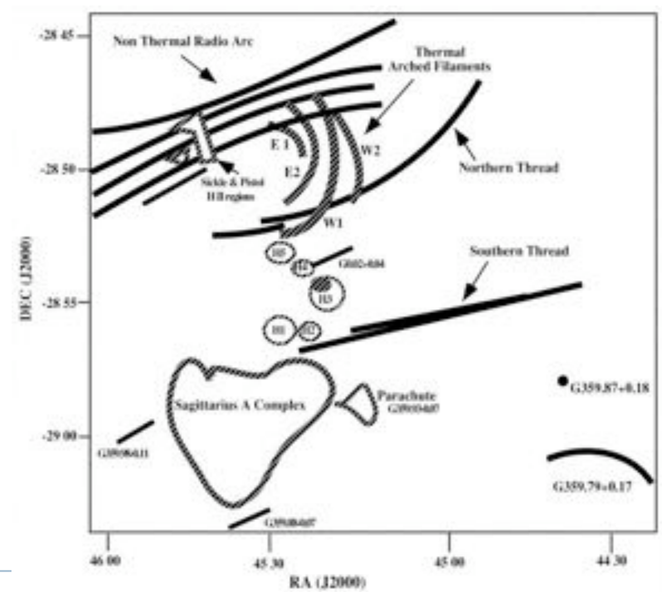
Counts proportional to luminosity function of *all* stars in M33 halo, corrected for contamination and completeness. TRGB at I = 20.7 gives distance modulus.

Galactic Center

- We'll talk about the center again when we discuss AGNs
- The optical view:

- The VLA 1.4 Ghz view:





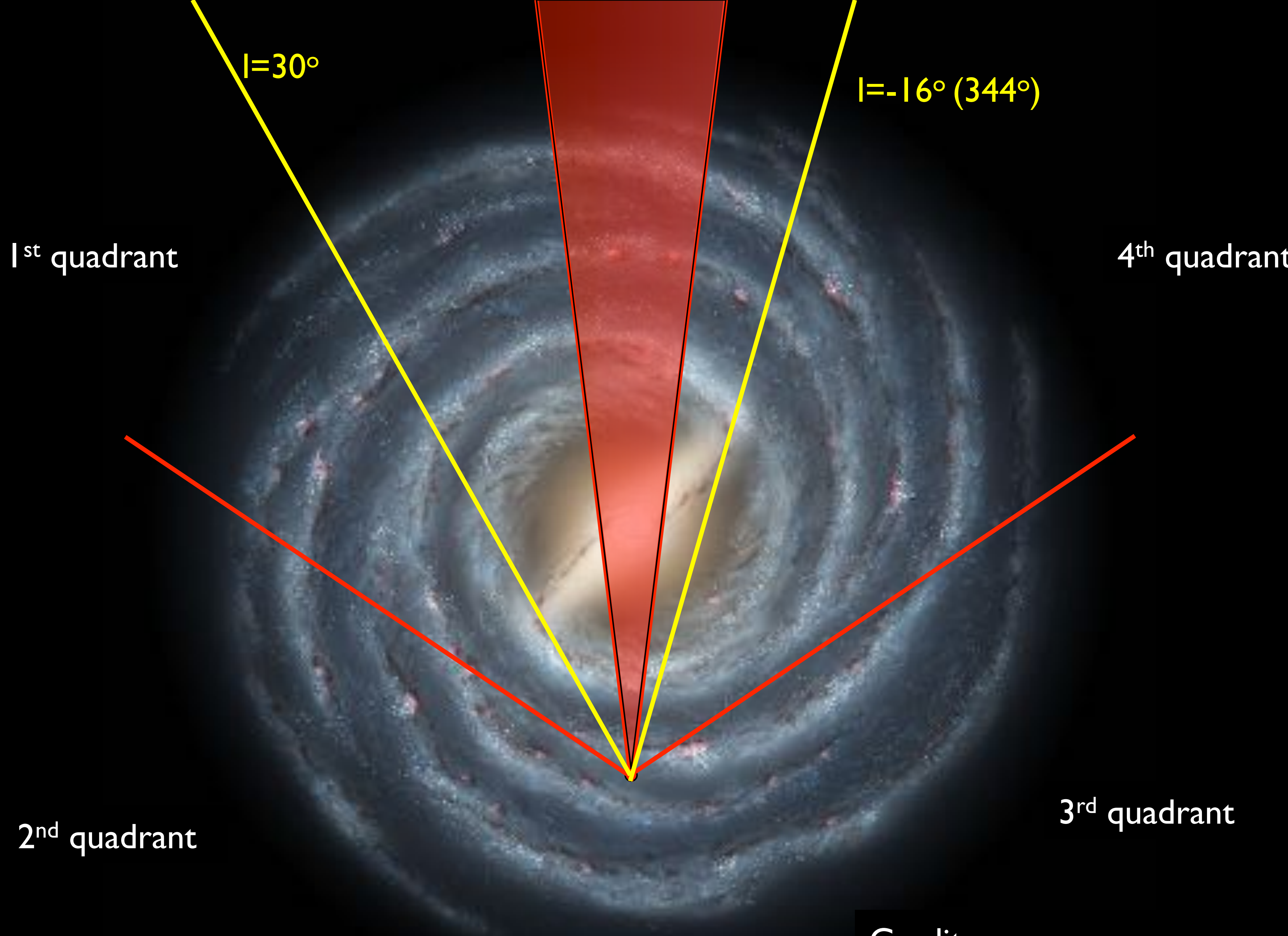
Galactic Center: Distance

- Use RR Lyraes + other stellar tracers
  - Use the globular cluster population, OH/IR stars in the bulge
  - Get mean distances → 8.5 kpc
- Proper motion studies of Sgr A*
  - Look for maser emission
  - Follow maser proper motion + observed velocity
    → distance (7.5 kpc)

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.

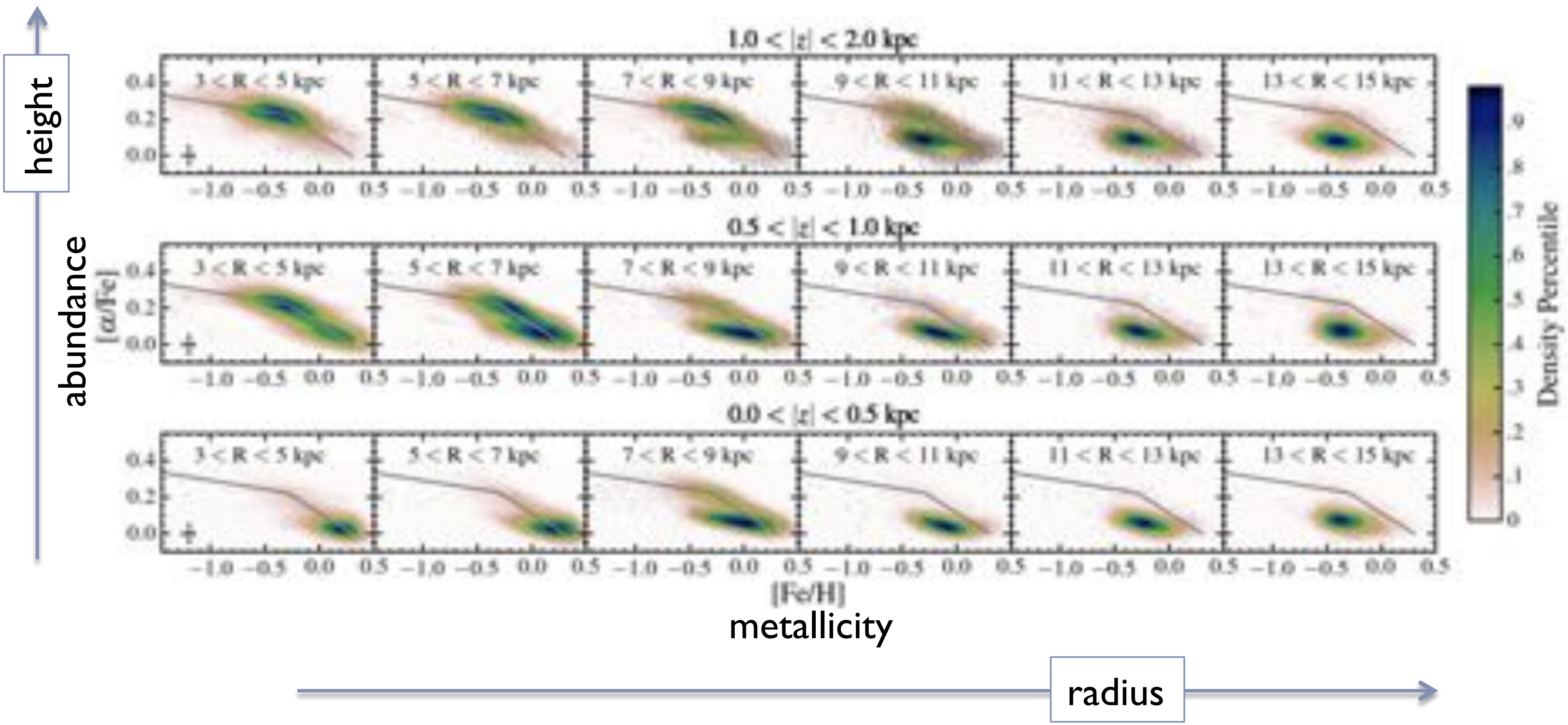


Galactic Longitude Asymmetry

Credits:
Robert Hurt (SSC/JPL/NASA)
Bob Benjamin (UWW)

Chemical Cartography

- The APOGEE-1 view from SDSS-III

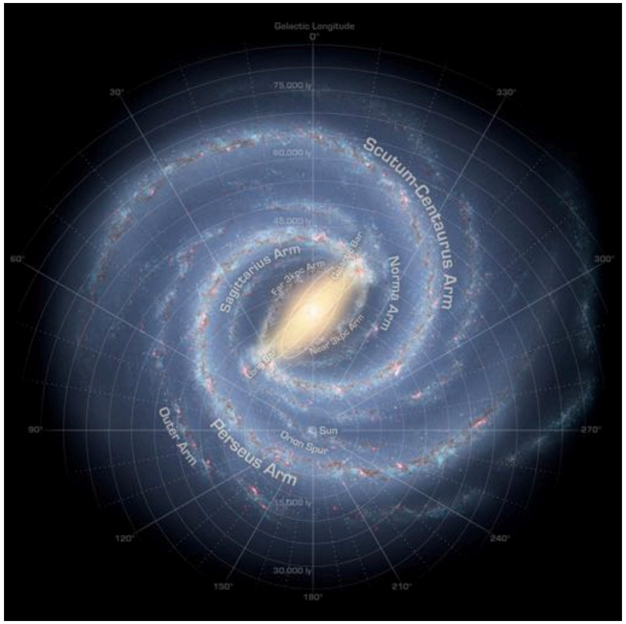


- Also: RAVE, SEGUE, GALAH/HERMES, APOGEE-2

Hayden+'15

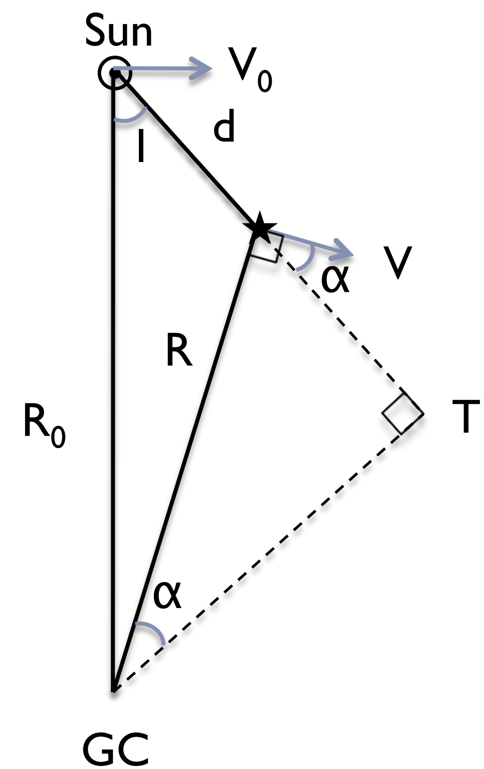
Galactic Rotation: A Simple Picture

- 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.



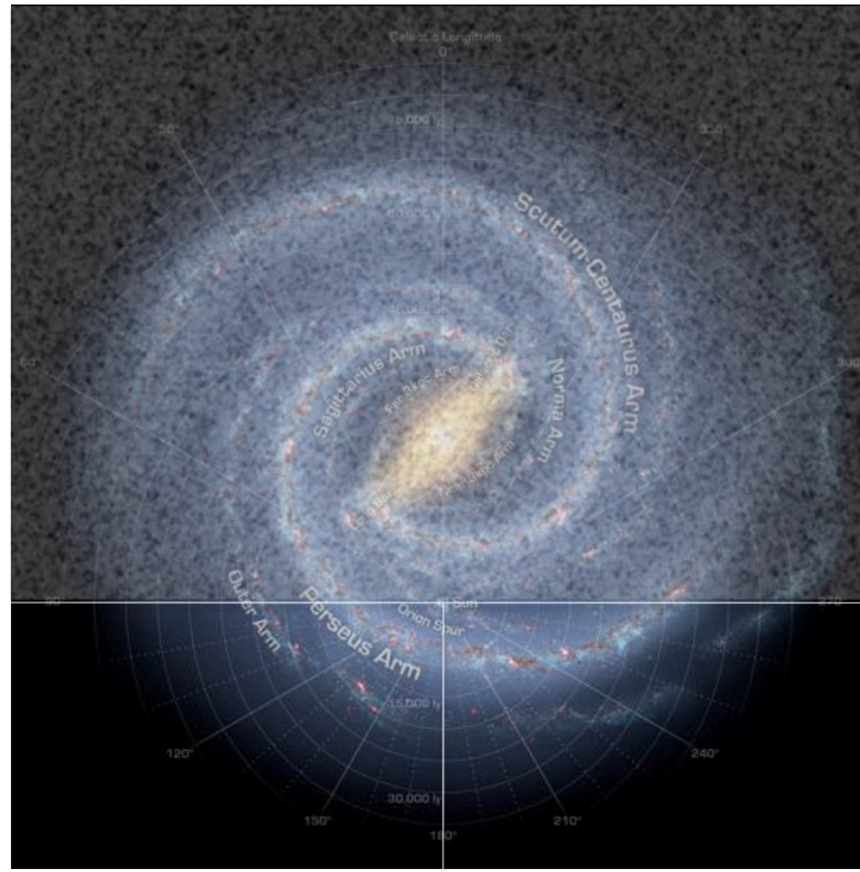
Relative motion of stars

- 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

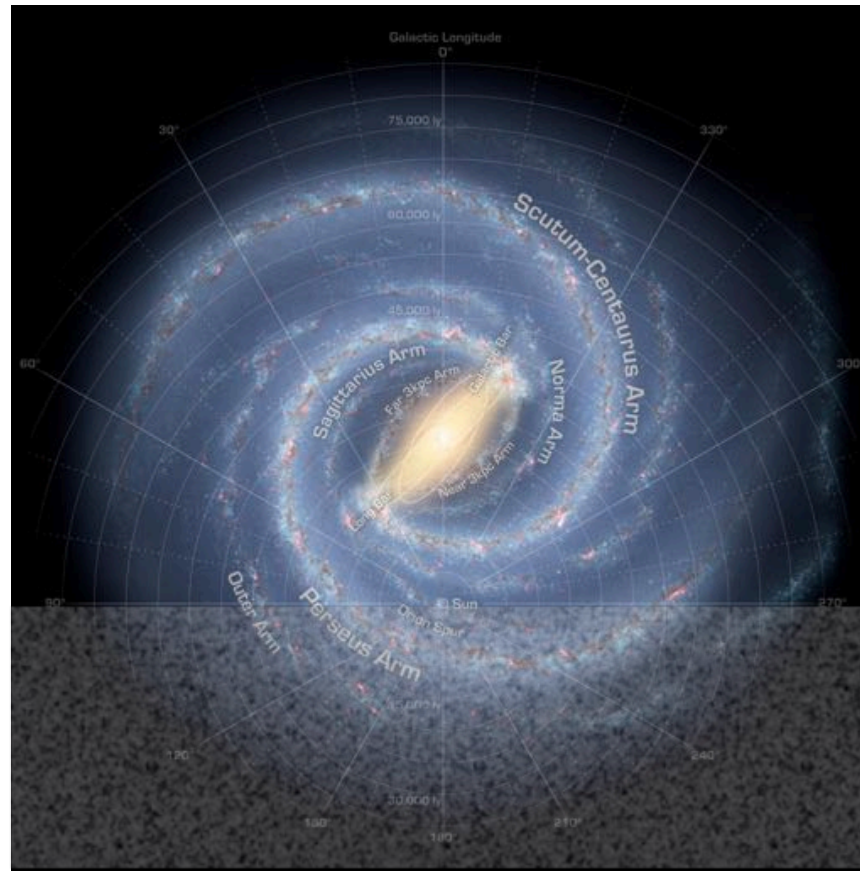
- $90° \leq l \leq 180°$
  - larger d
  - $R > R_0$
  - $\omega_*{}^* < \omega_0$
    - this means increasingly negative radial velocities
- $180° \leq l \leq 270°$
  - V_R is positive and increases with d



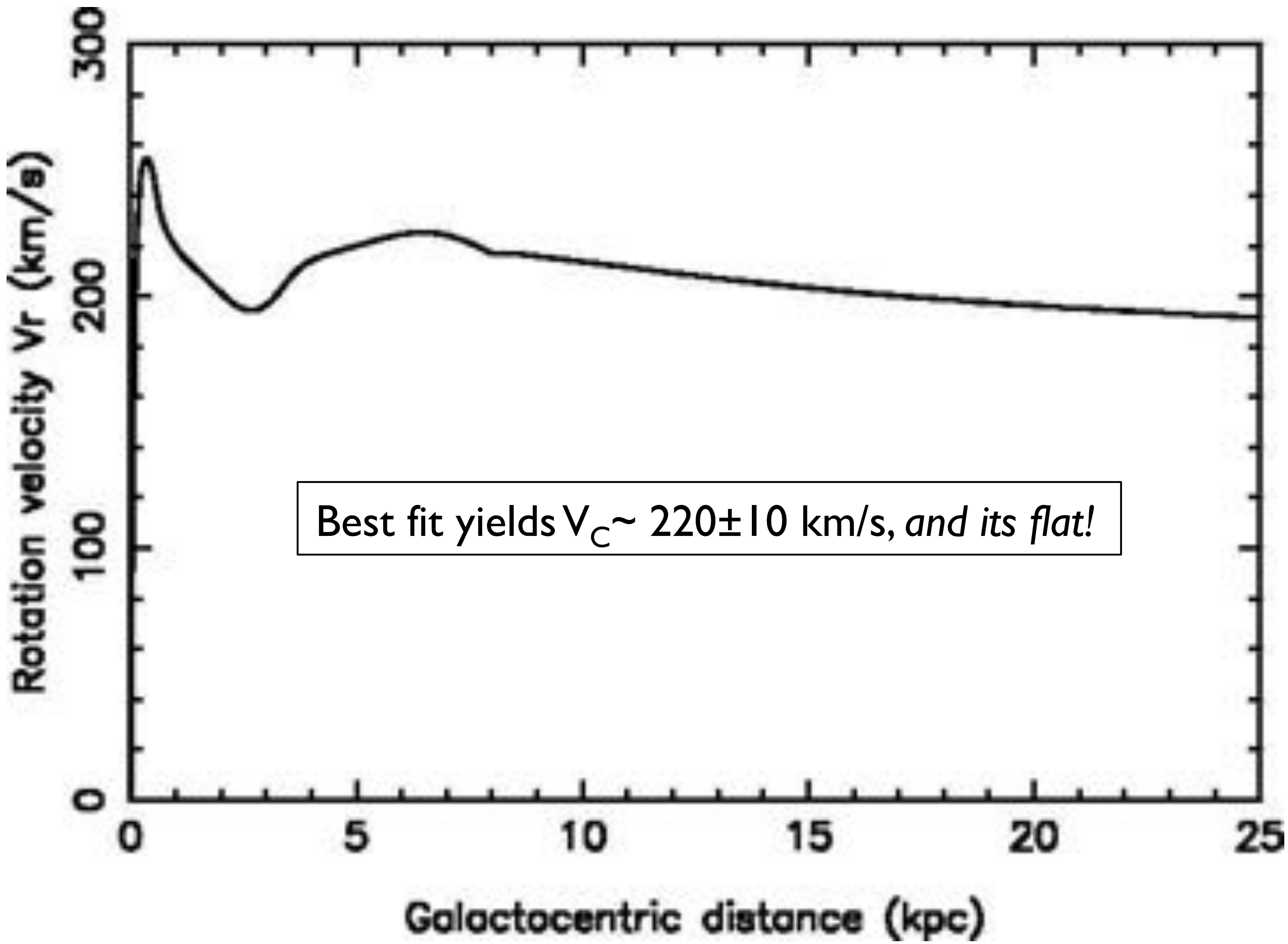
$90° \leq l \leq 180°$ $180° \leq l \leq 270$

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)

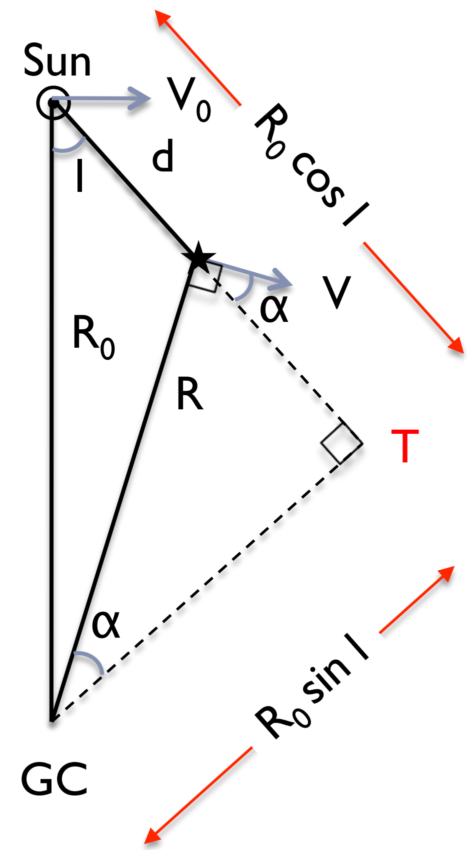
Galactic rotation

- 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 $\omega_0 = V_0/R_0 = 29 \pm 1$ 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 $d \ll R_0$,
  - $(R_0-R) \sim d \cos(l)$
  - $V_R = A\ d \sin(2l)$
- where $A = \frac{1}{2}[(V_0/R_0) - (dV/dR)_{R0}]$
  - 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)
- B = -12.4 ± 0.6 km/s/kpc
  - A measure of angular-momentum gradient in disk
- $\omega_0 = V_0/R_0$ = A-B
- $(dV/dR)_{R0}$= -(A+B)
- Observations of local kinematics can constrain the global form of the Galactic rotation curve

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

- 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…

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:
  - $u_\odot = -\langle U_* \rangle$, $w_\odot = -\langle W_* \rangle$, $v_\odot = -\langle V_* \rangle + \langle v_* \rangle$

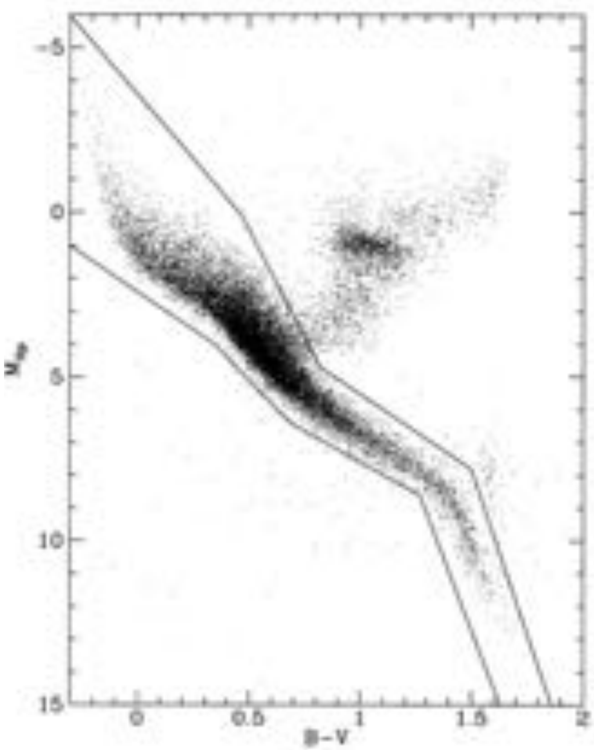
- Dehnen & Binney 1998 MNRAS 298 387 (DB88)
  - Parallaxes, proper motions, etc for solar neighborhood (disk pop only)
  - $u_\odot = -10.00 \pm 0.36$ km s^{-1} (inward; DB88 call this U_0)
  - $v_\odot = 5.25 \pm 0.62$ km s^{-1} (in the direction of rotation; DB88 call V_0)
  - $w_\odot = 7.17 \pm 0.38$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

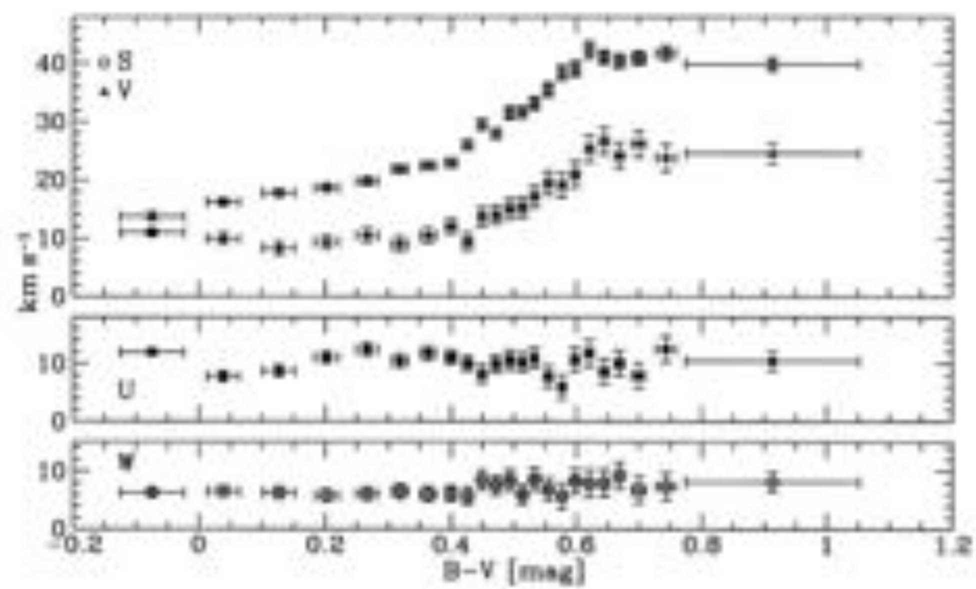
Solar Motion

- 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:





τ_{ms} ➔ mean age

Hipparcos catalogue: geometric parallax and proper motions

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

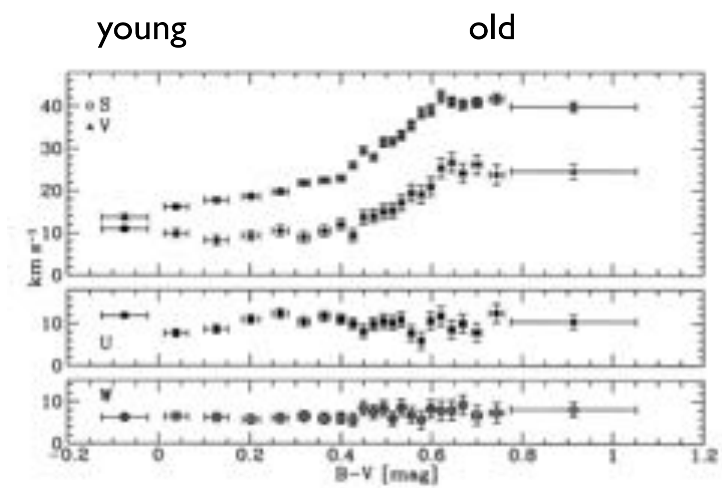
$S = S_0\,[1+(t/Gyr)^{0.33}]$ ← random grav. encounters

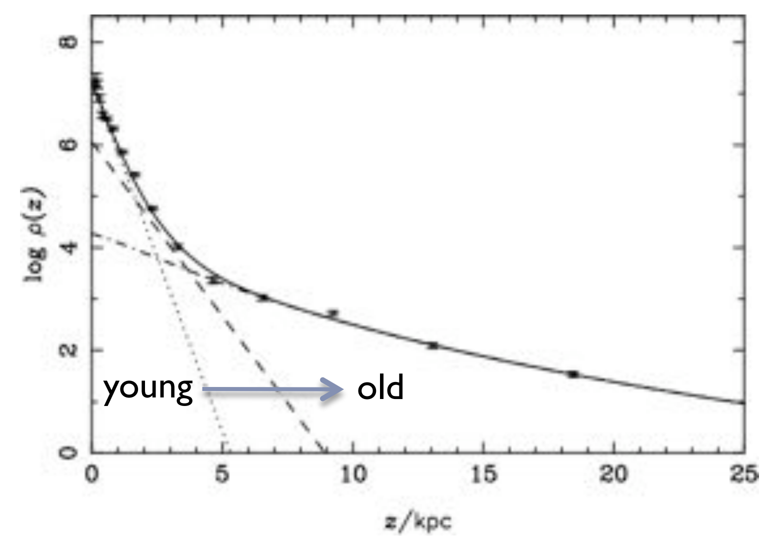
$S_0 = 8$ km s^{-1} ← why might this be?

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

Parenago's Discontinuity: the disk

- The disk is observed to be well described by a double exponential in radius (R) and vertical height (z)
- Revisit nomenclature from lecture 6 to be consistent with S&G:
  - $\rho(R,z) = \rho_0 \exp(-z/h_z) \exp(-R/h_R)$
    - ρ is matter density, e.g., in stars $\rho_* = n_* \times m_*$
  - Integrate $\rho(R,z)$ in z to get $\Sigma(R)$, e.g. $M_\odot\ pc^{-2}$
    - $\Sigma(R) = \int \rho(R,z)\, dz$
  - Multiply by the mass-to-light ratio ($M/L = \Upsilon$) to get I(R), the surface-brightness : $I(R) = \Upsilon^{-1} \times \Sigma(R)$
    - $\mu(R)$ often is used to denote surface-brightness in magnitudes arcsec^{-2}.
    - $\mu(R,\theta)$ would be surface-brightness at location R,θ in the disk (cyclindrical coordinates)
  - Integrate $\Sigma(R)$ in R to get total mass within a given radius M(R), … or I(R) to get total light
    - $M(R) = 2\pi \int \Sigma(R)\, r\, dr$
- Why is the distribution exponential in radius?
  - This is hard to answer definitively, but it is an observed fact.
- Why is the distribution exponential in height?
  - Here we will attempt to get a better physical standing in coming lectures.





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:

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

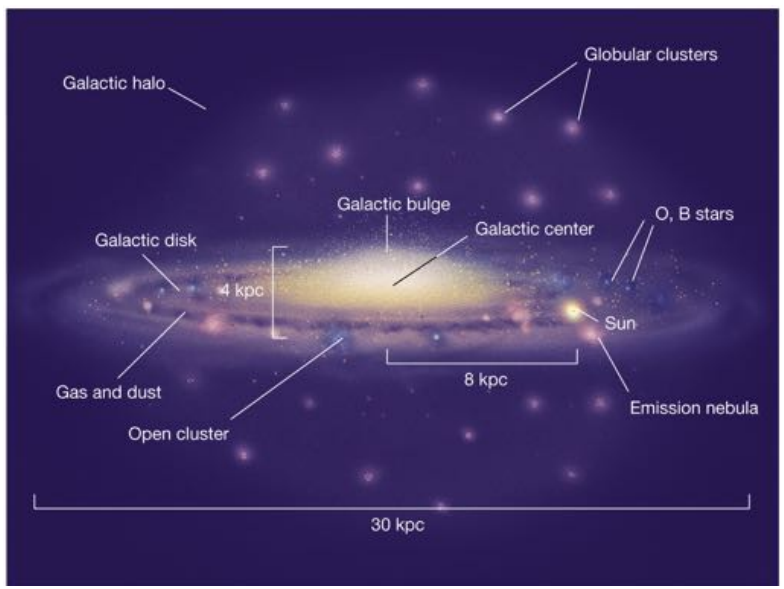
or, $\sigma_{los} = ((v - \underline{v})2)^{1/2}$

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)

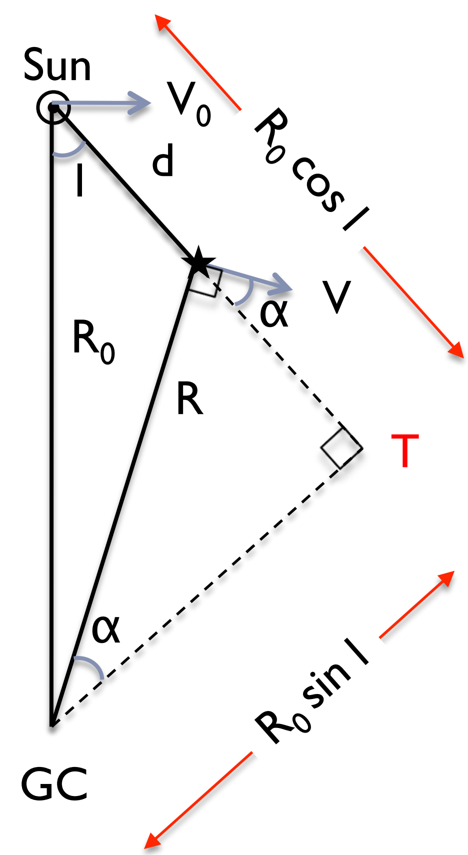
Globular Cluster Population

- 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

- Gas:
  - Good because the MW is optically thin at CO (mm) and HI (21cm) wavelengths
  - Bad because you have to use the tangent method –
    - essentially impossible to measure distances
- Stars:
  - Good because you can measure distances directly
  - Bad because it is difficult to measure distances for distant or faint stars
  - Bad because traditional studies are done in optical, which can't penetrate mid-plane dust
  - … enter the Sloan Digital Sky Survey (SDSS):



Measuring Galactic Rotation: Example

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

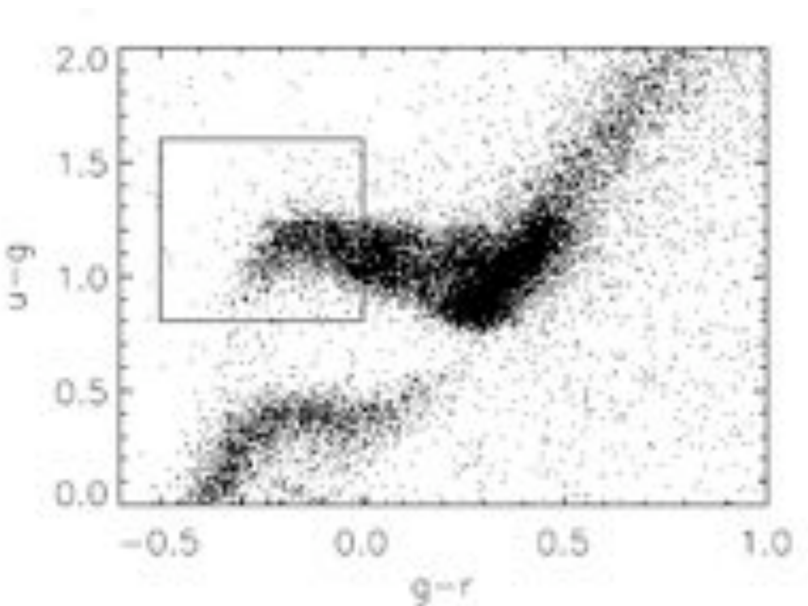
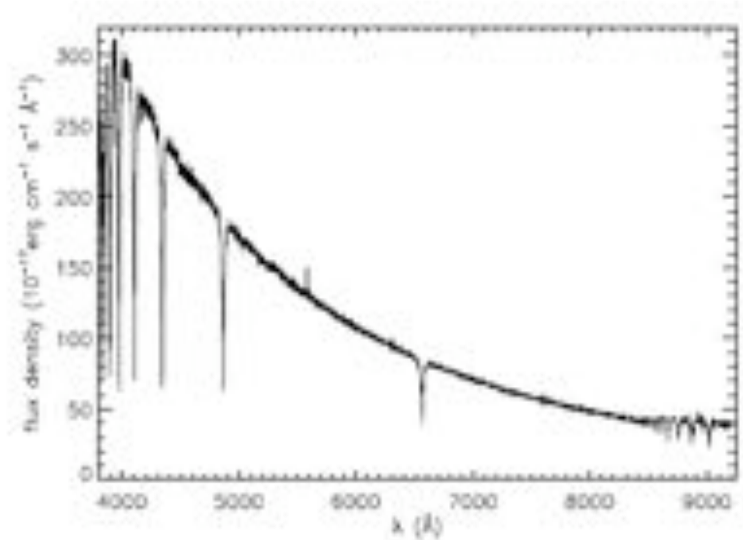


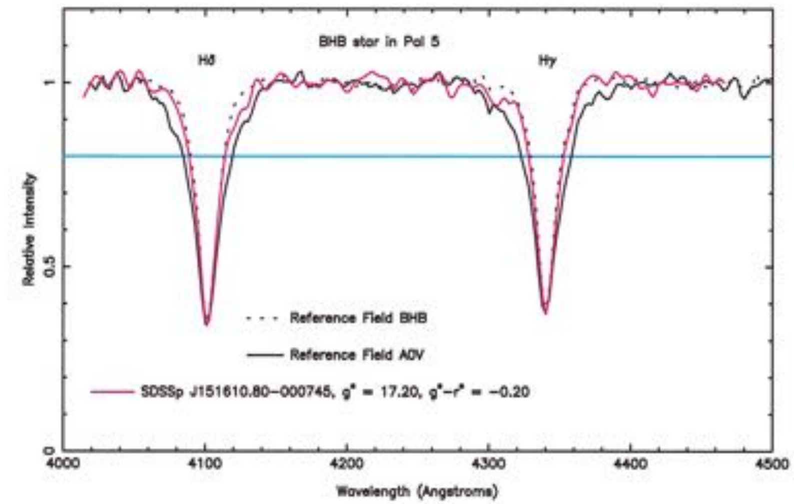
Fig. 1.—SDSS color-color diagram showing all spectroscopically targeted objects that were subsequently confirmed as stars. The large Balmer jump of A-type stars places them in the region where our "color-cut" selection box is drawn. This color selection approach follows Yanny et al. (2000).

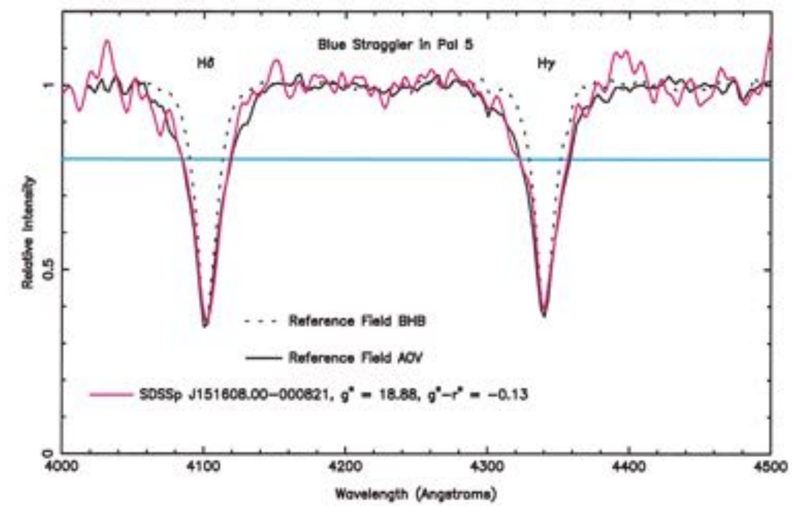


Xue et al. 2008

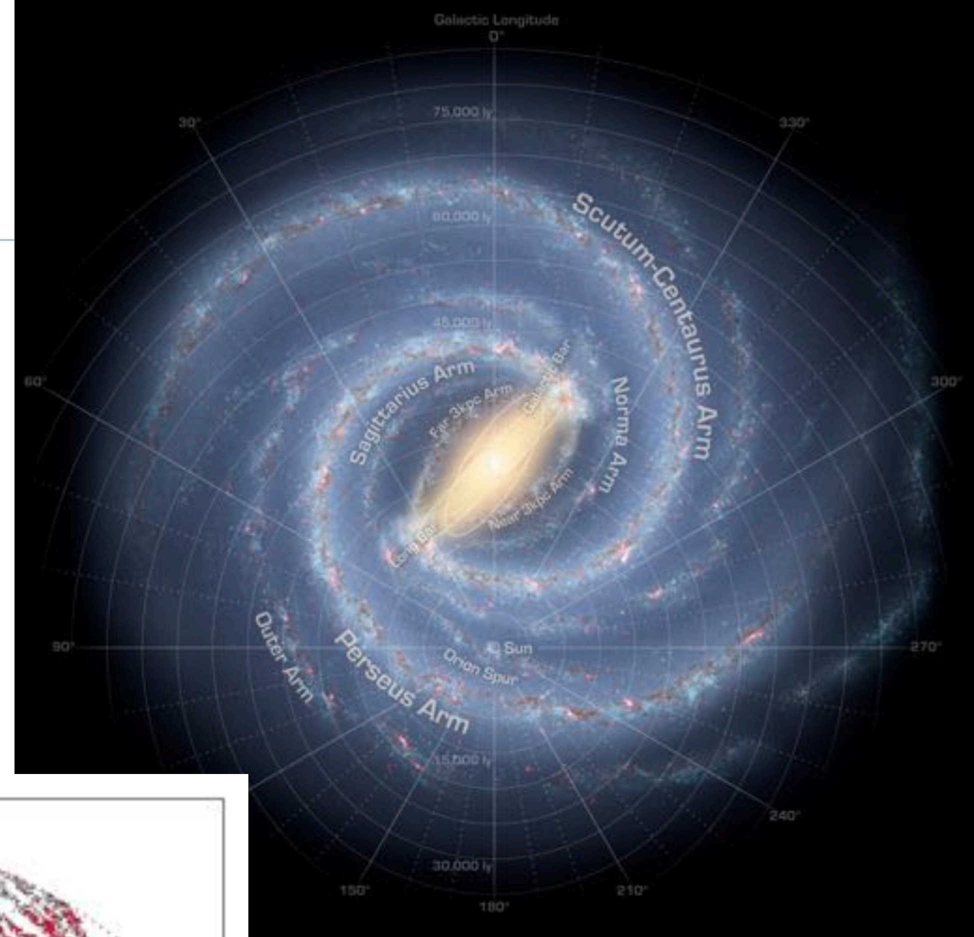
Measuring Galactic Rotation: Example

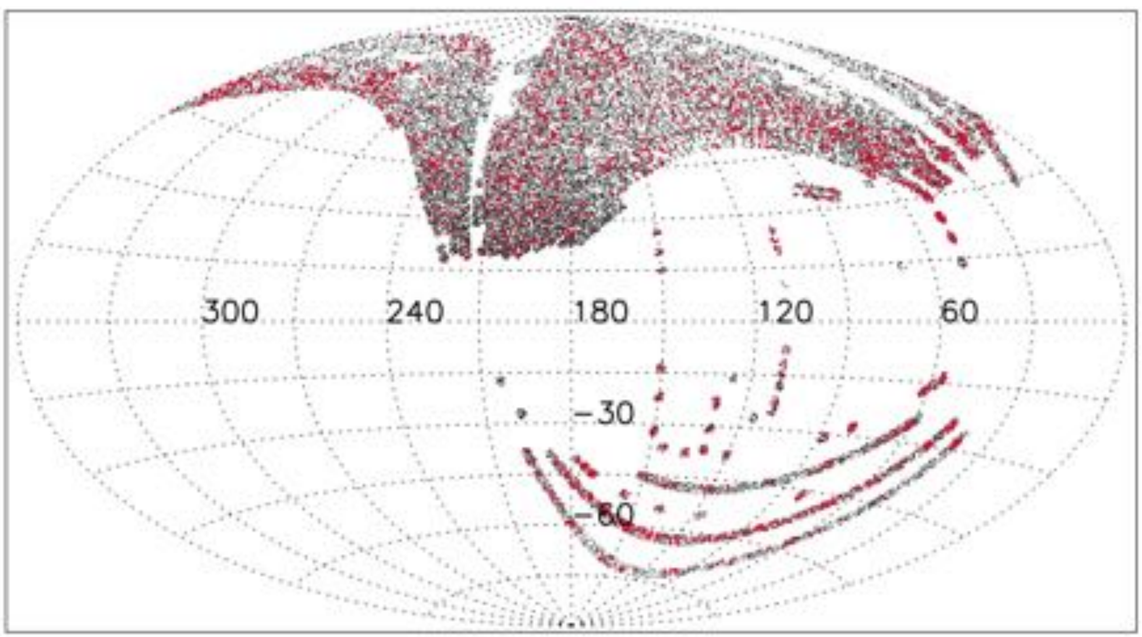
- Distinguish between blue horizontal branch stars and blue stragglers (MS) so the luminosity is known
- Infer distances





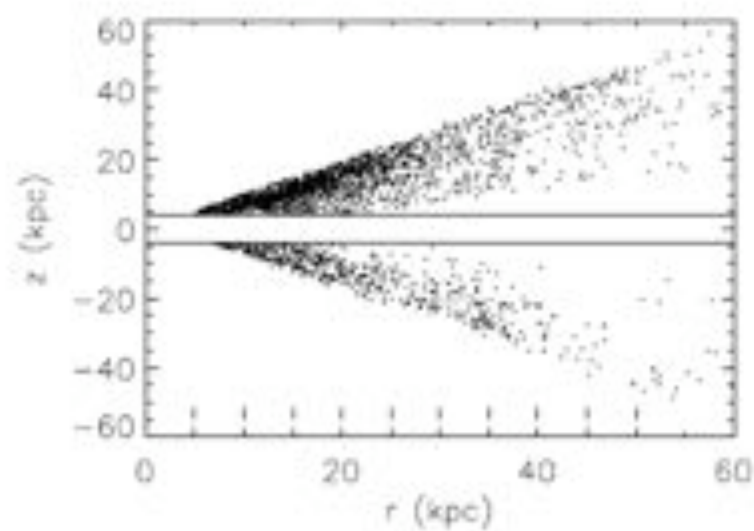
Sight Lines

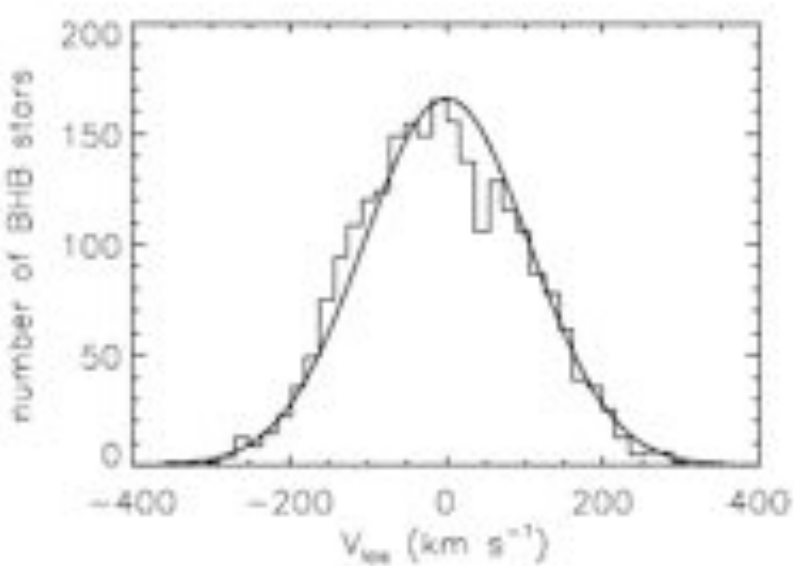

Galactic Longitude
0°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
30°
60°
90°
150°
180°
210°
240°
270°
300°
330°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Near 3kpc Arm
Norma Arm
Outer Arm
Perseus Arm
Sun
Orion Spur

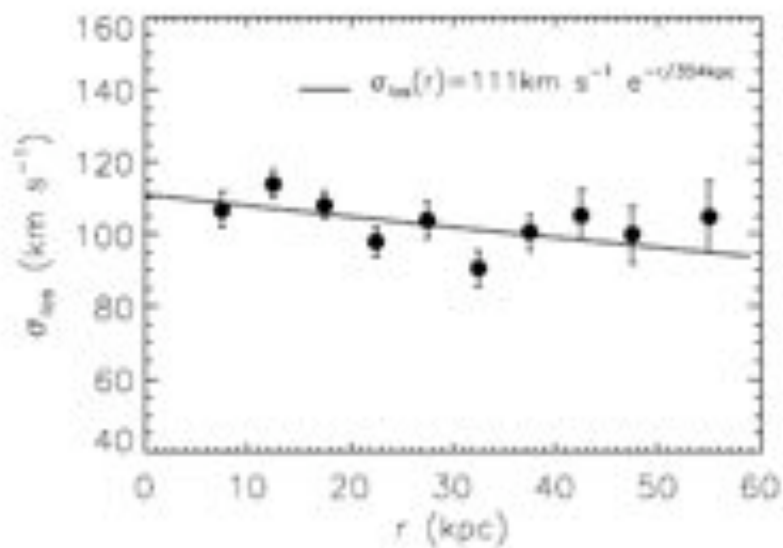

300
240
180
120
60
−30
−60

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.

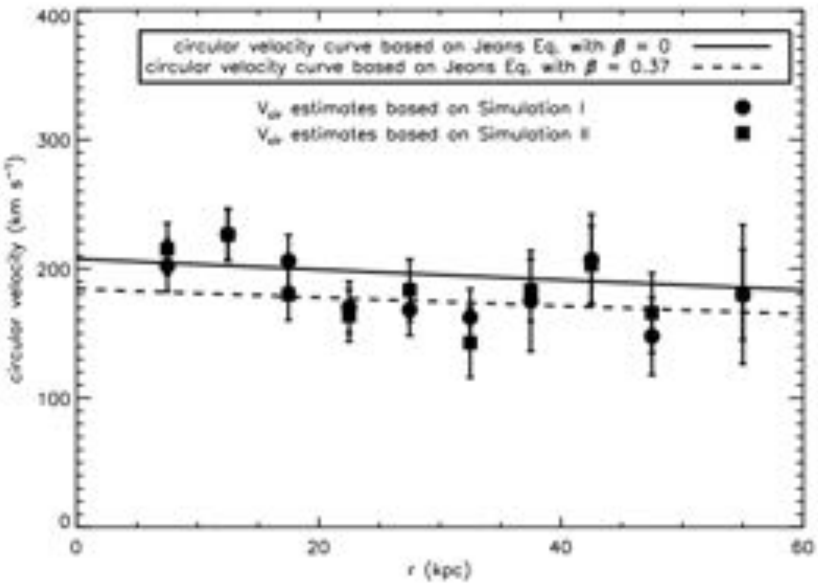


FIG. 15.—Distribution of circular velocity estimates, $V_{\rm cir}$, for two different simulated galaxies. The circles represent the $V_{\rm cir}$ estimates for the observed halo BHB stars based on simulation I, and the squares represent the $V_{\rm cir}$ estimates based on simulation II. The two lines 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:

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

with

$$\beta = 1 - \frac{\sigma_t^2}{\sigma_r^2}, \tag{9}$$

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 $\equiv \Upsilon_*$

➔ The IMF

➔ Missing physics