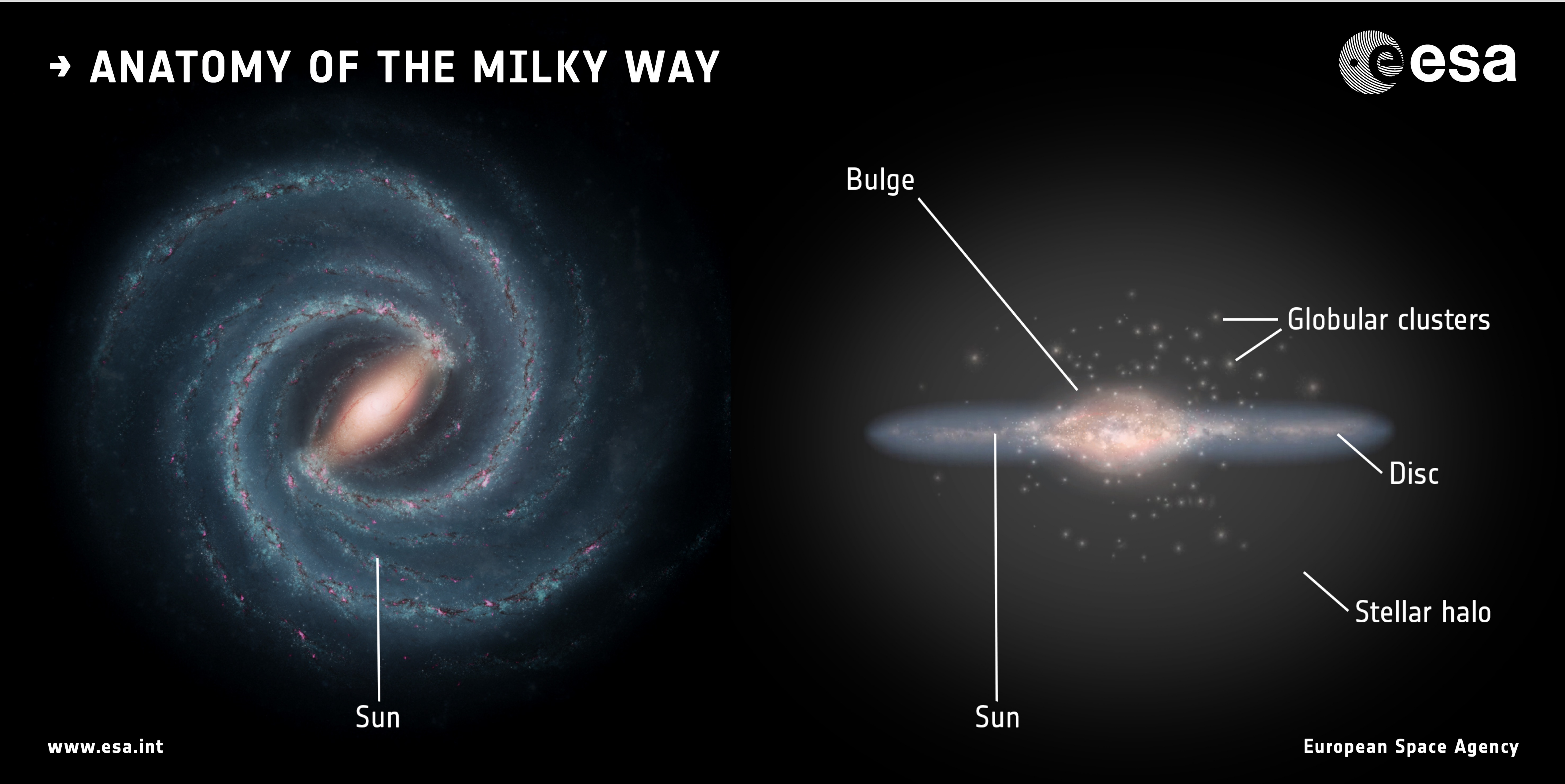
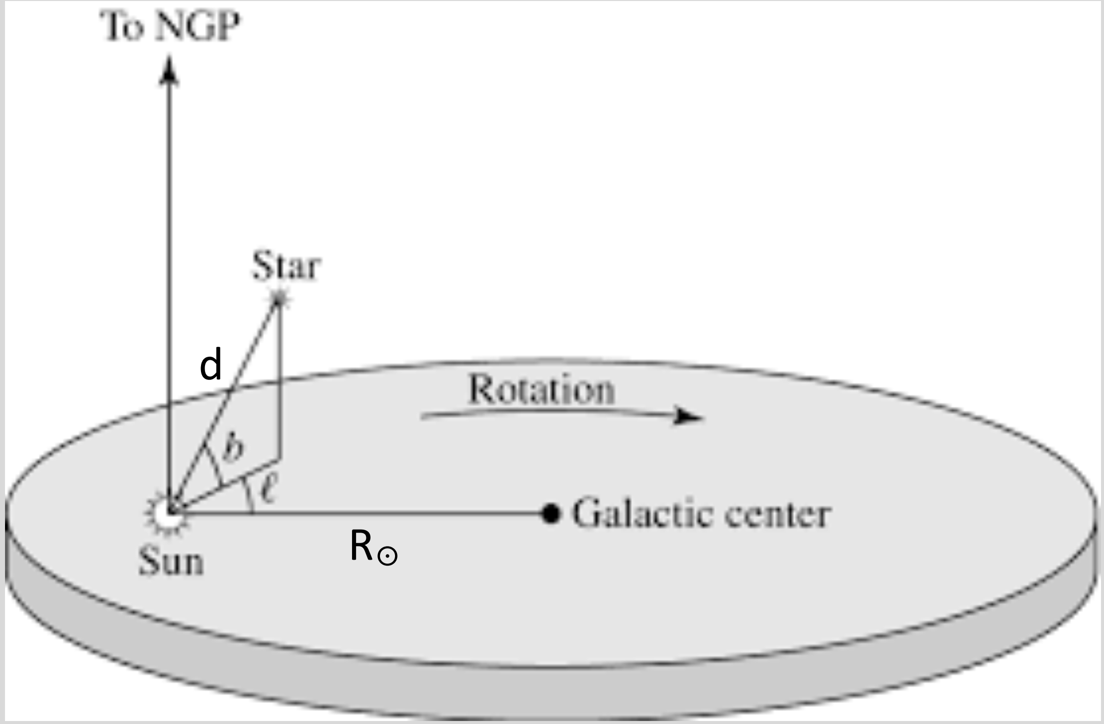
The Milky Way: A structural overview

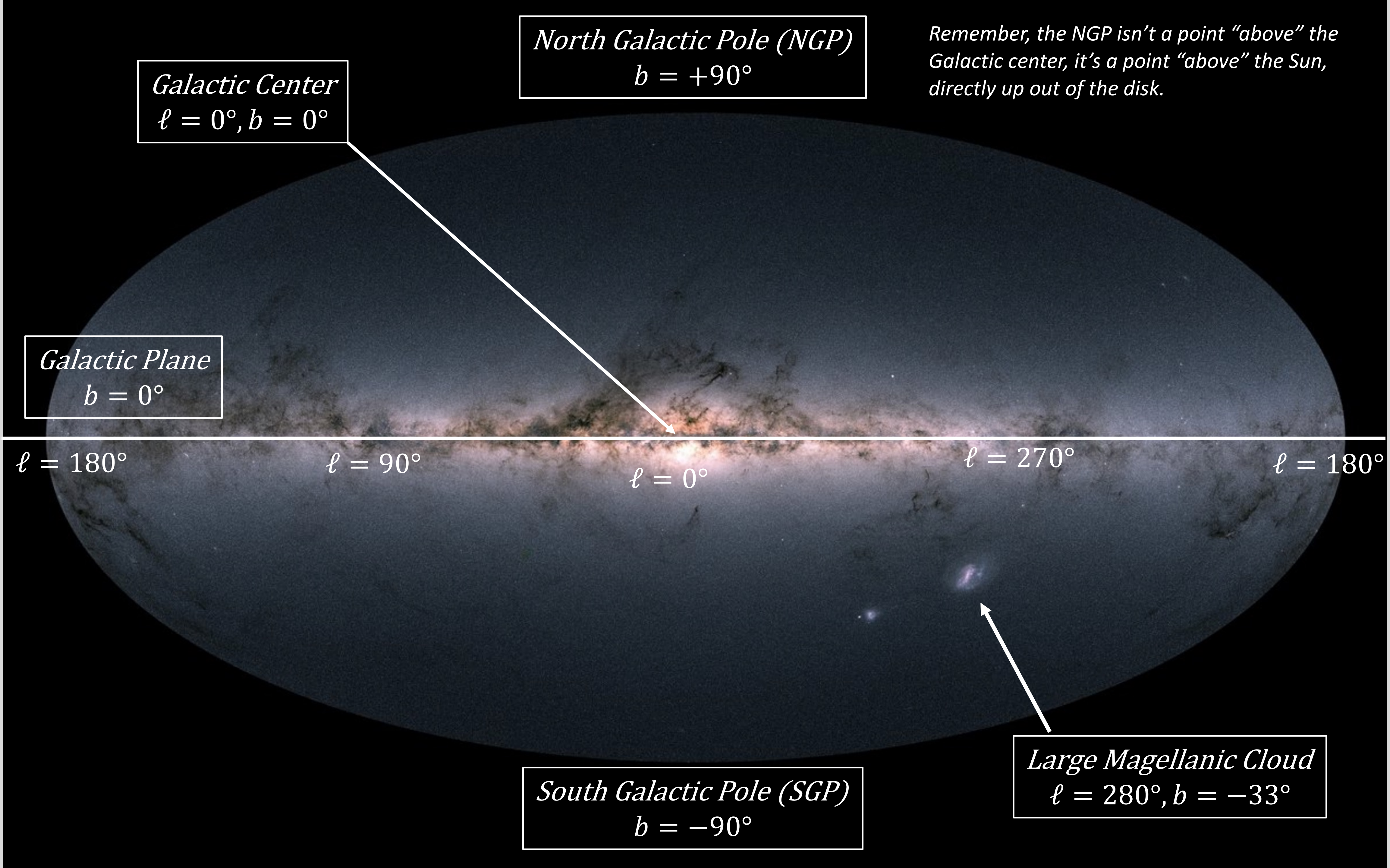


Galactic Coordinate Systems

Galactic (angular) coordinates

ℓ : galactic longitude (0 = galactic center, 90 = direction of rotation)
b : galactic latitude (above/below the plane)
(d : distance from Sun)




North Galactic Pole (NGP)
$b = +90°$
Remember, the NGP isn't a point "above" the Galactic center, it's a point "above" the Sun, directly up out of the disk.
Galactic Center
$\ell = 0°, b = 0°$
Galactic Plane
$b = 0°$
$\ell = 180°$
$\ell = 90°$
$\ell = 0°$
$\ell = 270°$
$\ell = 180°$
Large Magellanic Cloud
$\ell = 280°, b = -33°$
South Galactic Pole (SGP)
$b = -90°$

Galactic Coordinate Systems

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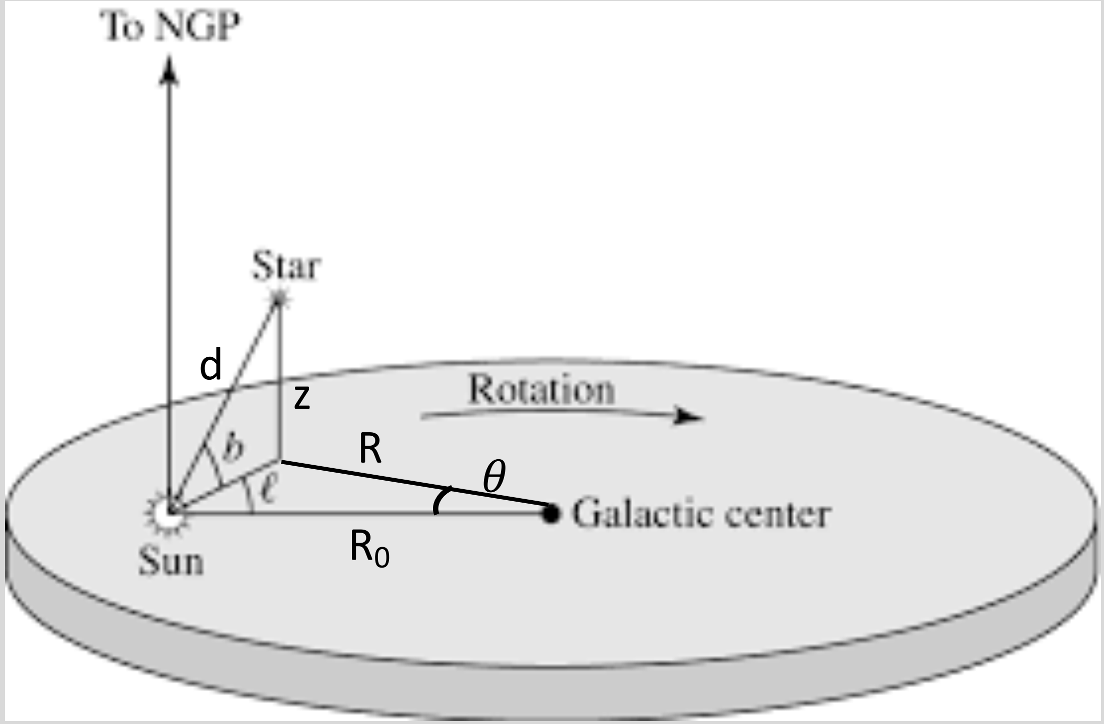
Physical cylindrical coordinates

R : radial coordinate (not to be confused with R_0!)
θ : angular coordinate
z : height above disk plane



Galactic Coordinate Systems

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Physical cylindrical coordinates

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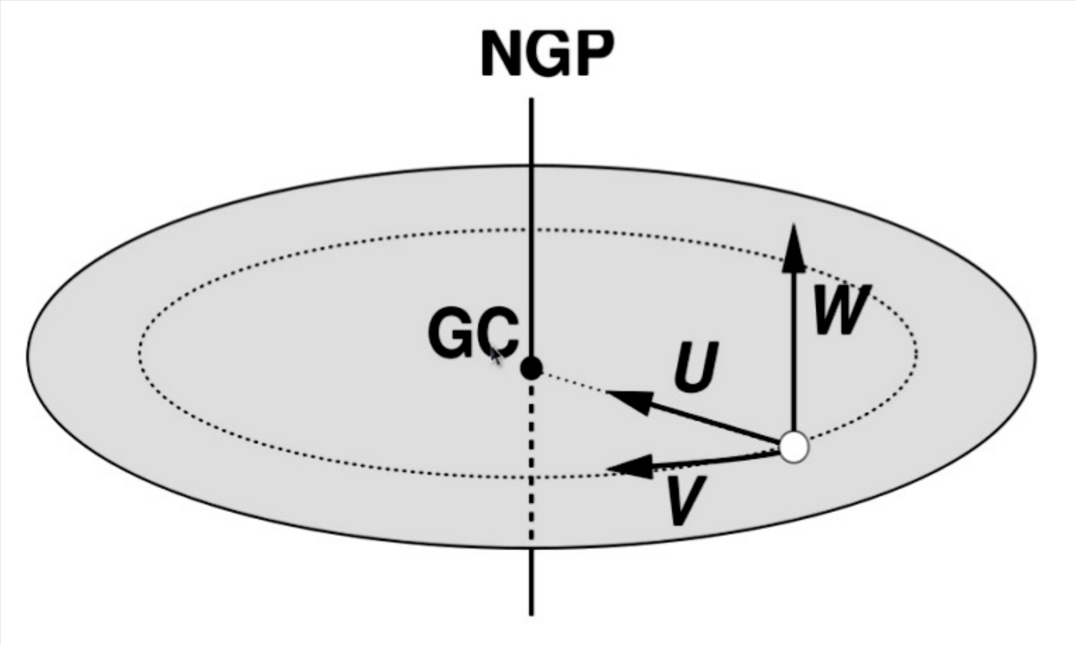
Kinematics (all in km/s)

U: R velocity (−dR/dt); positive ⇒ towards center
V: θ velocity (R dθ/dt); positive ⇒ direction of rotation
W: z velocity (dz/dt); positive ⇒ northwards

(+U,+V,+W) = (in, forward, up)



Important: V velocities are (usually) defined ***after*** *removing the circular velocity of the disk.*

So a star on a circular orbit will have V=0 km/s.

The Local Standard of Rest

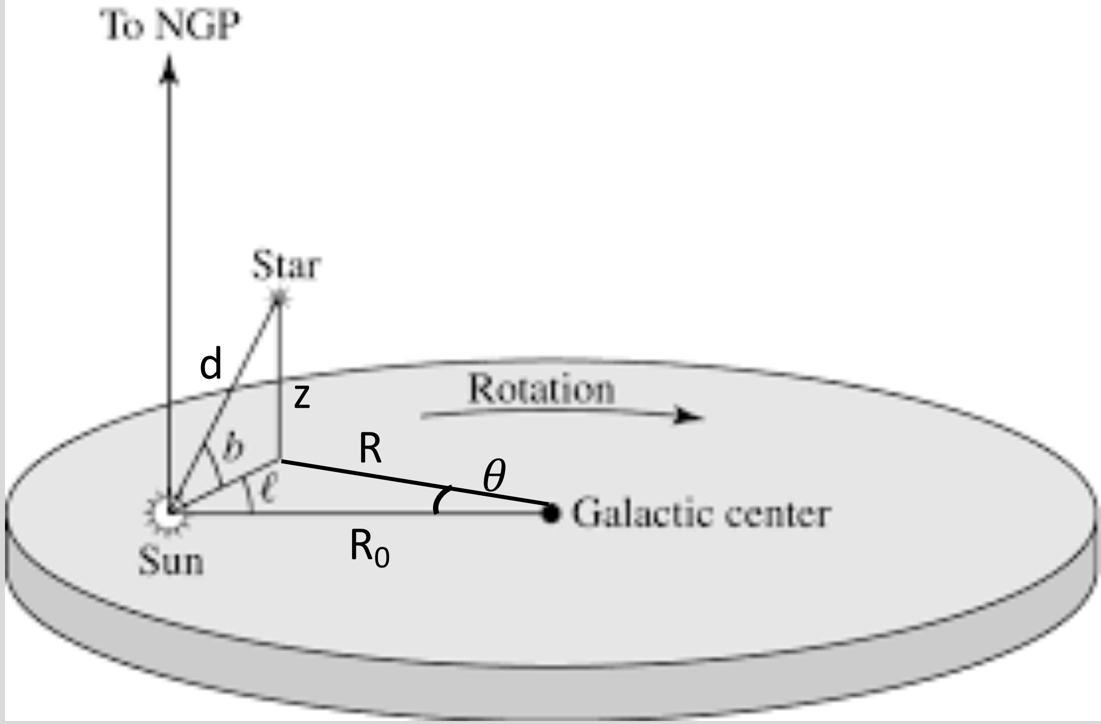
Imagine **a point at R_0 moving on a circular orbit** around the galactic center. This is called the **local standard of rest (LSR)**, and we want to measure the motion of stars with respect to this frame.

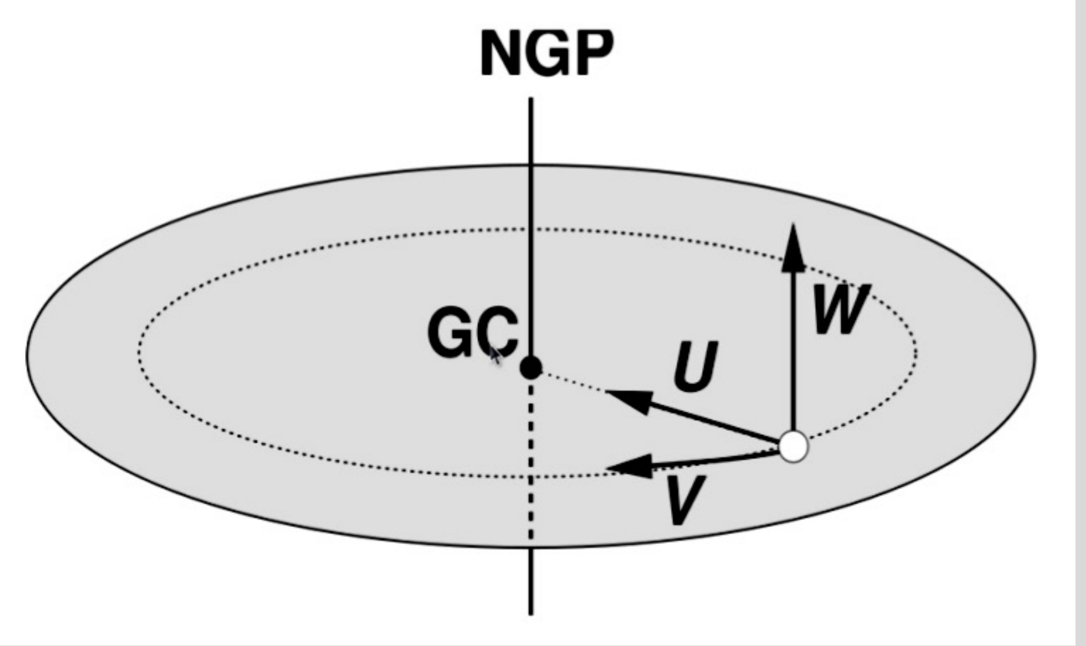
How do we measure the velocities of stars?

- line-of-sight radial velocity (v_{los} in km/s)
- proper motion (two sky components, in arcsec/yr)
- distance (d in pc; converts proper motion to speed)

These things give us the velocity of the star *with respect to the Sun*. We want velocities in the Galactic coordinate system *relative to the LSR*. This involves:

- Transformation of coordinates ("simple" geometry)
- Removal of the solar motion (surprisingly complex!)
  $(U_\odot, V_\odot, W_\odot) \approx (11,12,7)$ km/s





Stellar Kinematics and the Solar Motion

Disk stars move on roughly circular orbits, with relatively small random velocities, characterized by a Gaussian velocity dispersion in each coordinate.

These dispersions together define the "velocity ellipsoid": $(\sigma_U, \sigma_V, \sigma_W)$.

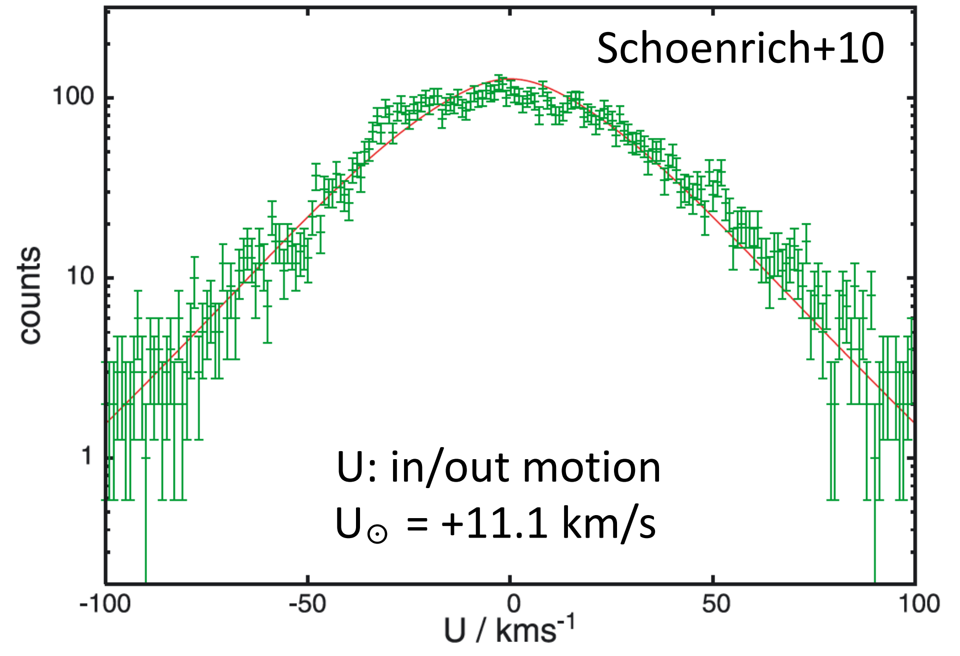
If, ***on average***, the local solar neighborhood moves with the LSR, nearby stars should have average $(\langle U\rangle, \langle V\rangle, \langle W\rangle) = (0,0,0)$.

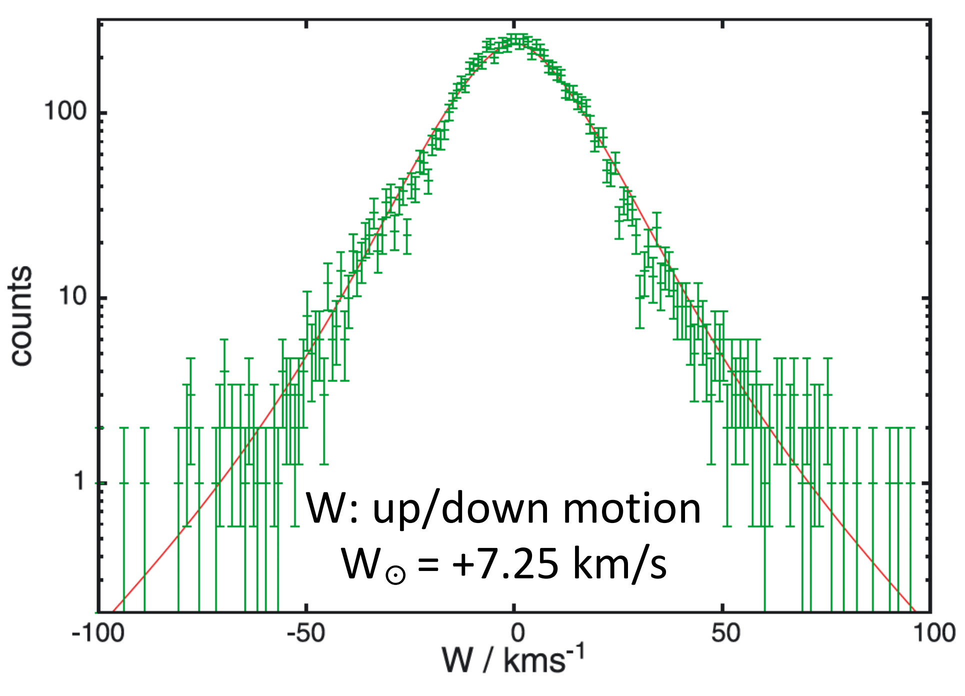
Measure velocity distributions, look for a non-zero mean velocity: this traces the Sun's motion.

U, W velocity distributions ***after*** correction for solar motion ⇒

The distributions are symmetric and Gaussian-like.
(Remember, a Gaussian plotted logarithmically is a parabola....)

The measured standard deviation is the velocity dispersion of the sample of stars.



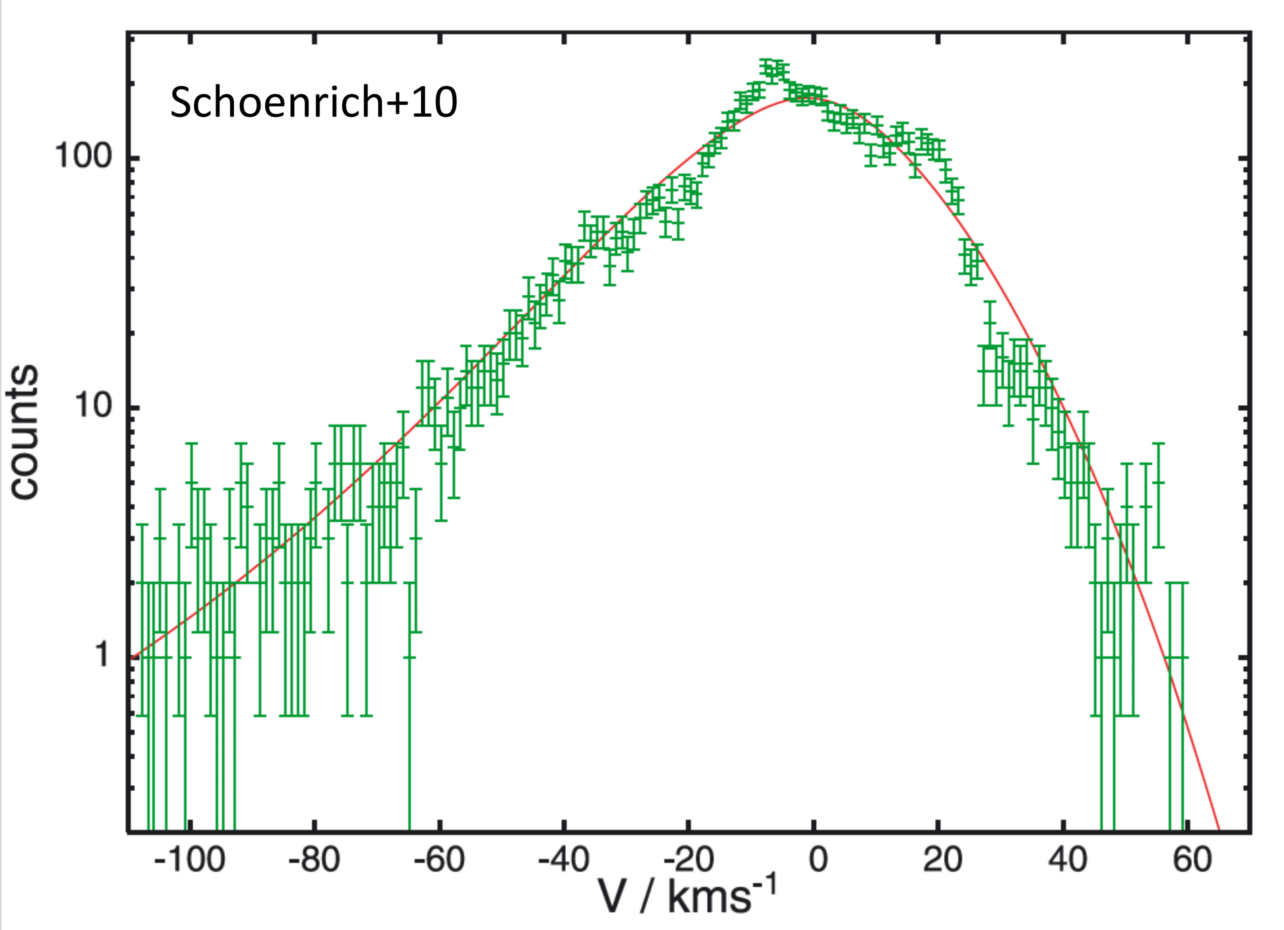


Measuring the Solar Motion: Asymmetric Drift

The distribution of velocities in V shows different behavior, the distribution of stellar V velocities shows many stars with negative V velocities (lagging the Sun's motion).

This is referred to as **asymmetric drift.**

What's going on?



Measuring the Solar Motion: Asymmetric Drift

Consider three stars on different orbits, each one passing through the solar circle (R_0):

Star A:

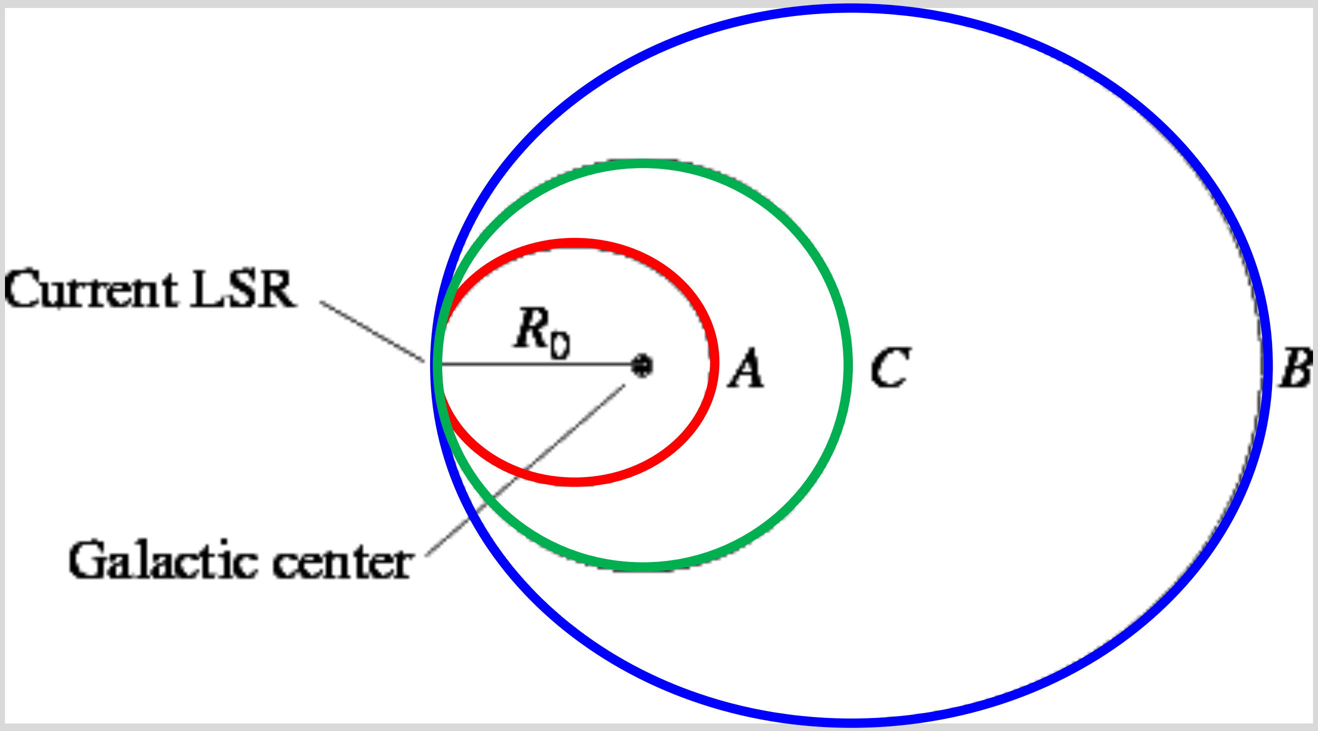
Elliptical orbit reaching R_0 at apocenter.
Stars move slowly at apo, so $v_\theta < v_{circ}$
This star lags the LSR ($V<0$)

Star B:

Elliptical orbit reaching $R_\odot$ at pericenter.
Stars move fastest at peri, so $v_\theta > v_{circ}$,
This star leads the LSR ($V>0$)

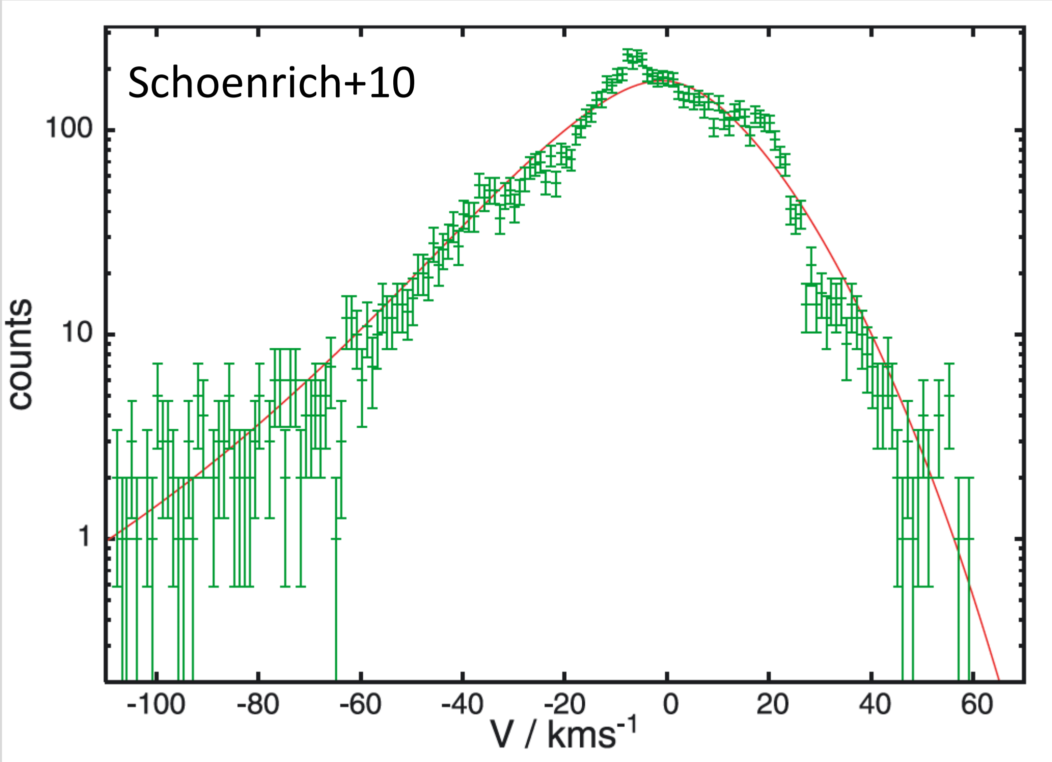
Star C:

Circular orbit at $R_\odot$ always
It moves at the circular speed $v_\theta = v_{circ}$
This star moves with the LSR ($V=0$)



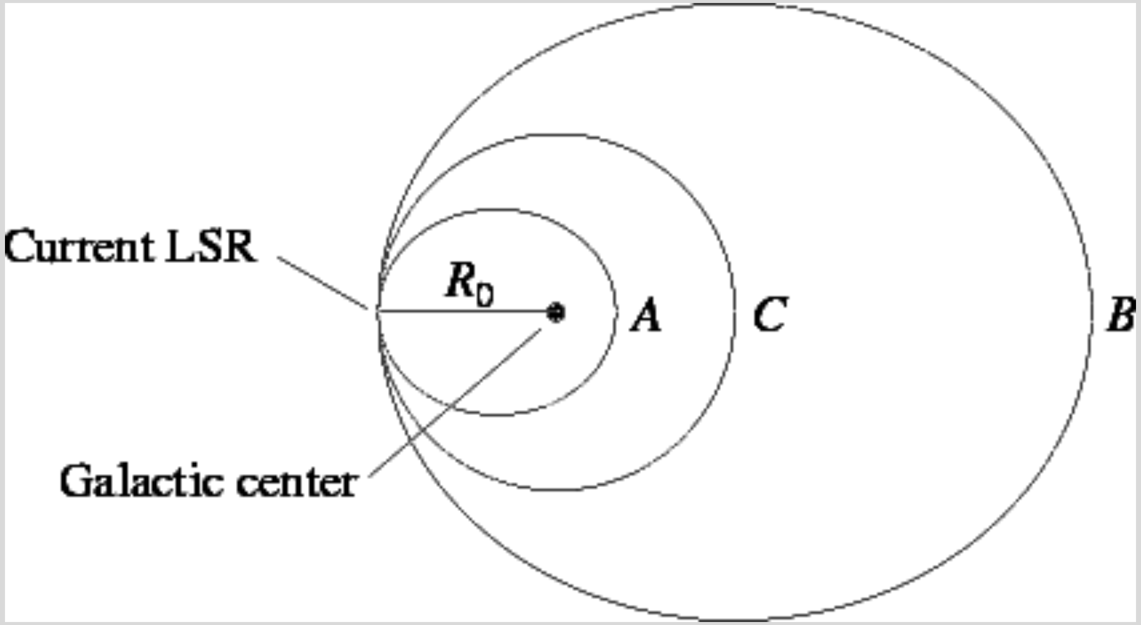
Measuring the Solar Motion: Asymmetric Drift

The distribution of velocities in V shows different behavior, a long tail of stars to negative velocities: **asymmetric drift.**



Consider stars on three orbits, each through the solar circle ($R_\odot$):

- Star A: $v_\theta < v_{circ}$, lags the LSR
- Star B: $v_\theta > v_{circ}$, leads the LSR
- Star C: $v_\theta = v_{circ}$, moves with the LSR



In the plot of velocities, we see more "laggers" (negative velocities) than "leaders" (positive velocities). Why is this?

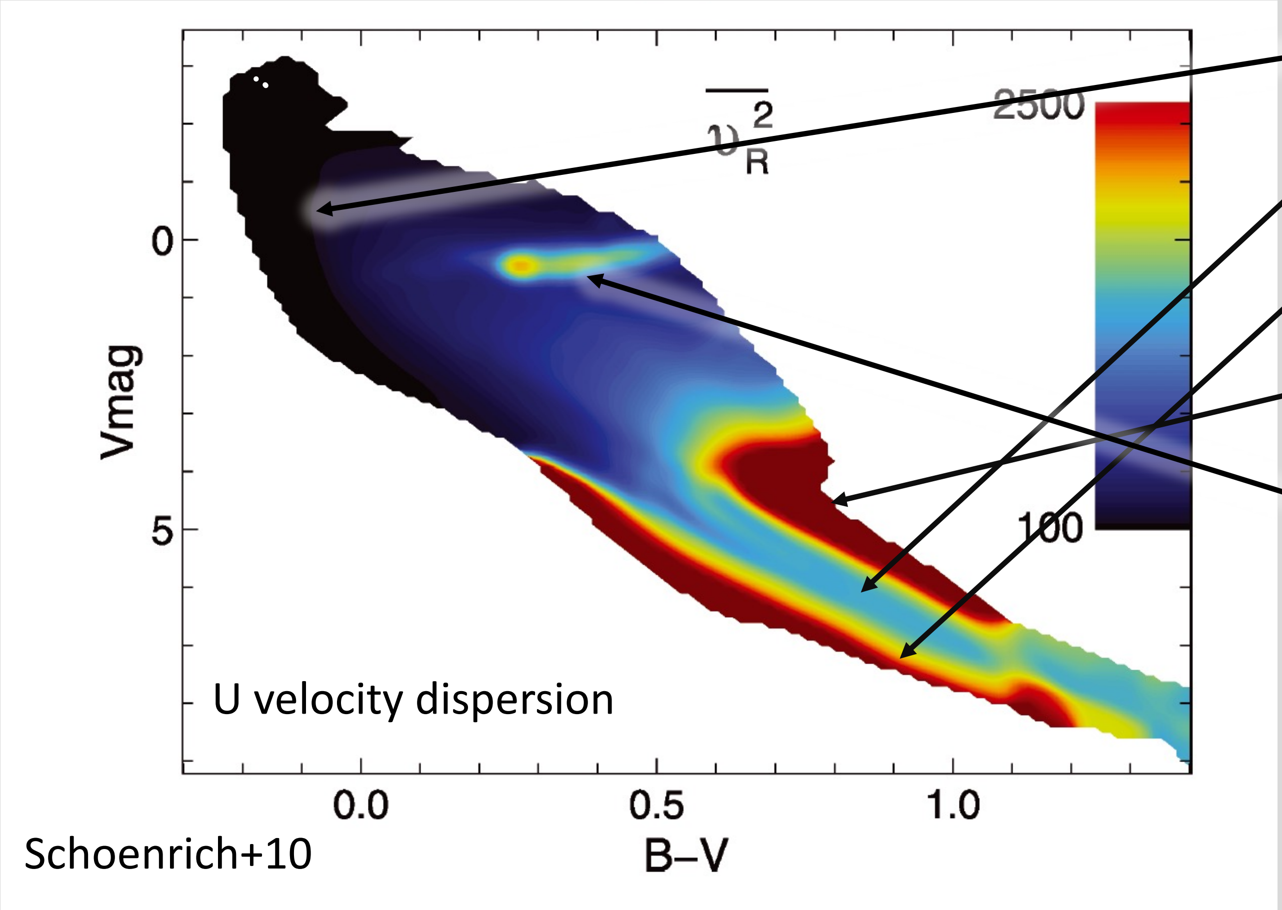
The density of stars is higher as you go inwards, so in the solar neighborhood there are more stars inside us coming out than outside is coming in. More laggers than leaders.

The mean V velocity is biased, so we can't simply use <V> to determine solar motion.

U velocity dispersion for stars along the color-magnitude diagram.

Remember, U velocity is galactocentric radial velocity ("in-out").

(Remember: a *star* doesn't have a velocity dispersion, but a *population of stars* does....)



Upper main sequence: very low dispersion

Lower main sequence: moderate dispersion.

Metal poor main sequence ("subdwarfs"): high dispersion

Evolving subgiants: high dispersion

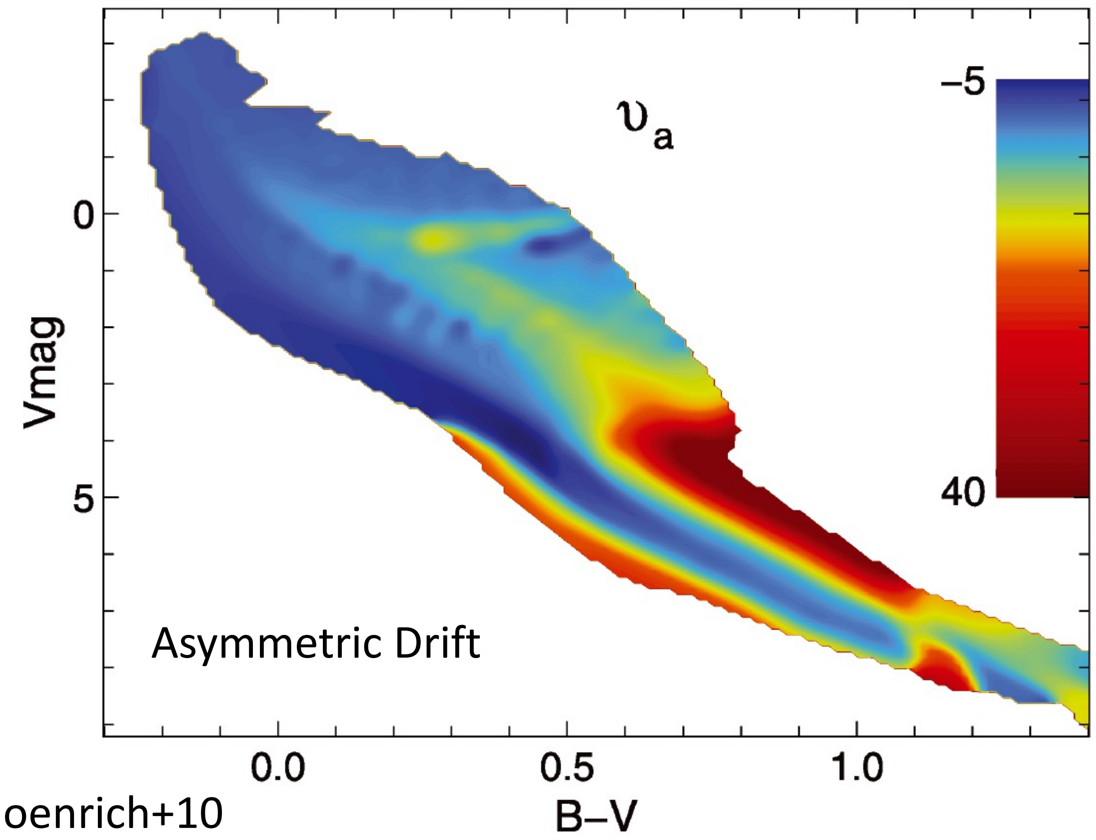
Horizontal branch stars: high dispersion

What is the common theme here? ***Mean stellar age.***

note that $\overline{v_R^2} \approx \sigma_U^2$
In other words, this is showing the U (radial) velocity dispersion

Asymmetric Drift Velocity for stars along the color-magnitude diagram.

Mean V-velocity ("forward-back")



Schoenrich+10

Older populations have higher random velocities and lag the LSR more.

Argues that stars are born on circular orbits, but as time goes by, their trajectories are scattered more and more: higher random motions.

What would scatter stars?

Over time, repeated gravitational encounters with giant molecular clouds or spiral arms acts to slowly scatter stars off their initially circular orbits.

→ Older stars have higher random motions.

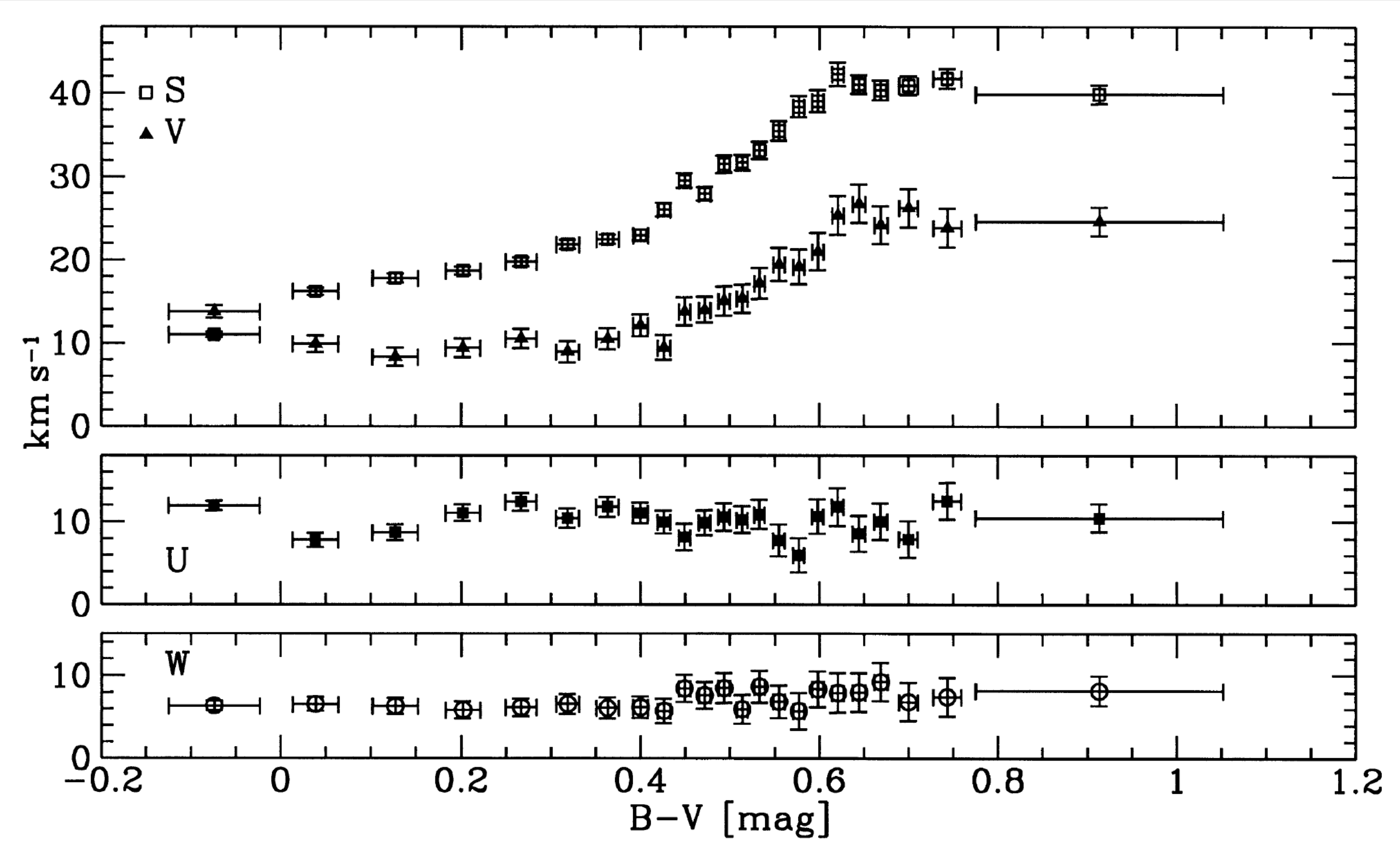
Measuring the Solar Motion: Effect of Asymmetric Drift

Average (U,V,W) velocities and total velocity dispersion (S) as a function of color ⇒

Blue stars: young
Red stars: mix of ages

Things to note:

- Average U and W velocities are uncorrelated with color. These are giving good estimates of $U_\odot$ and $W_\odot$.
- Average V velocity strongly correlated with color. Measures a combination of $V_\odot$ and drift velocity. Drift velocity is smaller for young populations.



Dehnen & Binney 98

Measuring the Solar Motion: Correcting for Asymmetric Drift

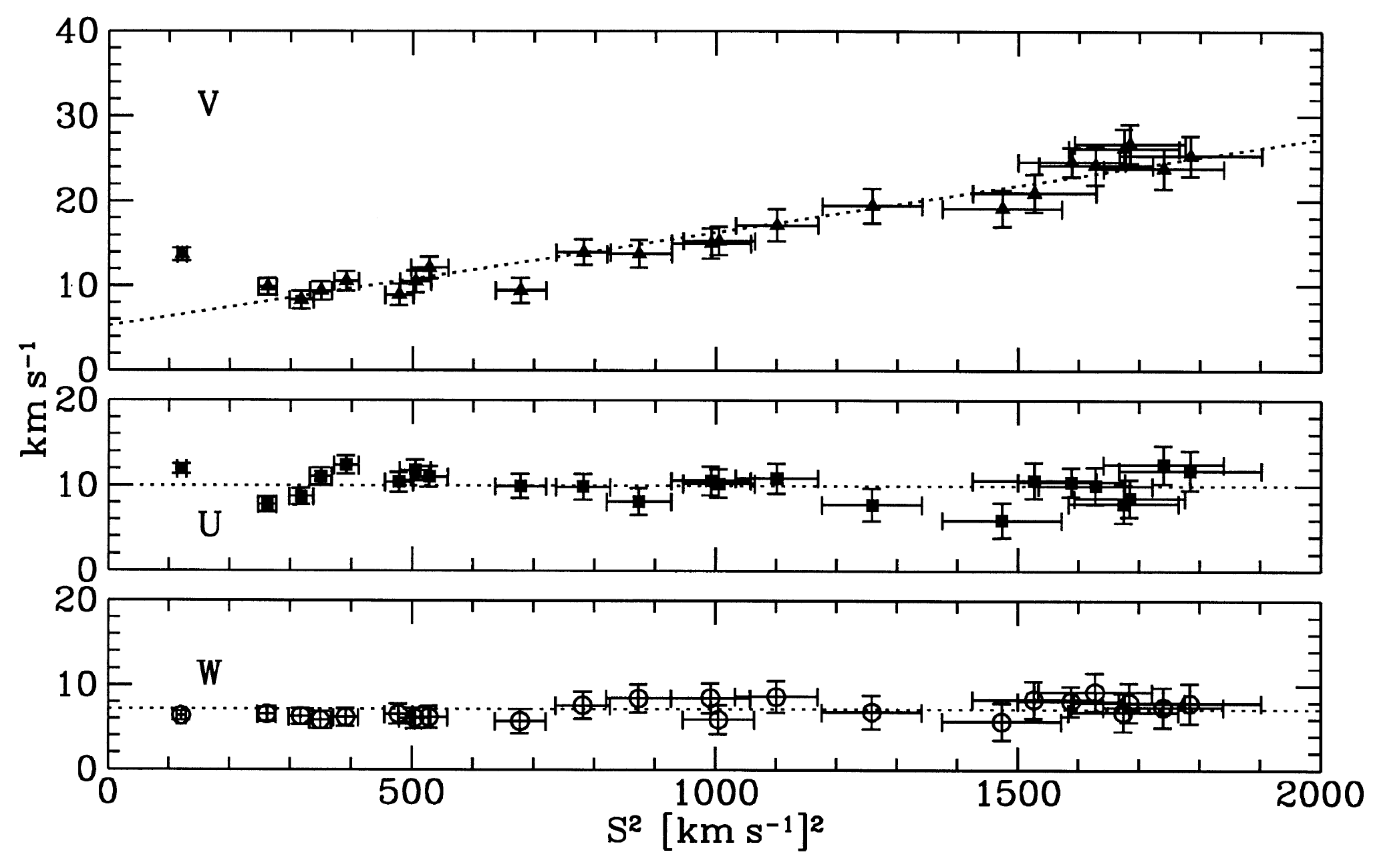
Define the solar motion with respect to a hypothetic population with zero velocity dispersion.

Plot mean motion as a function of dispersion; solar motion is defined by the y-intercept (zero velocity dispersion).

This dataset (Dehnen & Binney 98):
$(U_\odot, V_\odot, W_\odot) = (+10,+5,+7)$ km/s

Updated analysis (Schoenrich+10):
$(U_\odot, V_\odot, W_\odot) = (+11,+12,+7)$ km/s

With the Sun's motion solved, we can characterize stellar kinematics using a well defined framework: the LSR.



Inferred solar motion (U,V,W) as a function of total velocity dispersion (S)
Dehnen & Binney 98

Velocity dispersion of stars: Recap

An **individual star** has a position and a velocity, giving it a six dimensional coordinate in **phase space**: $(\vec{x}, \vec{v})$

The kinematics of **stellar populations** in the solar neighborhood can be described using mean velocities and velocity dispersions (spread in velocities).

- Mean velocities, after correction for solar motion: $(\langle U\rangle, \langle V\rangle, \langle W\rangle) = (0, v_a, 0)$
- Velocity dispersions: $(\sigma_U, \sigma_V, \sigma_W)$
  also known as the velocity ellipsoid

Velocity dispersion is a measure of random (non-circular) motion.

Velocity dispersion and asymmetric drift all rise with mean age of the population being studied.

Inference: Stars are born on circular orbits, then scattered to higher random motion with time.