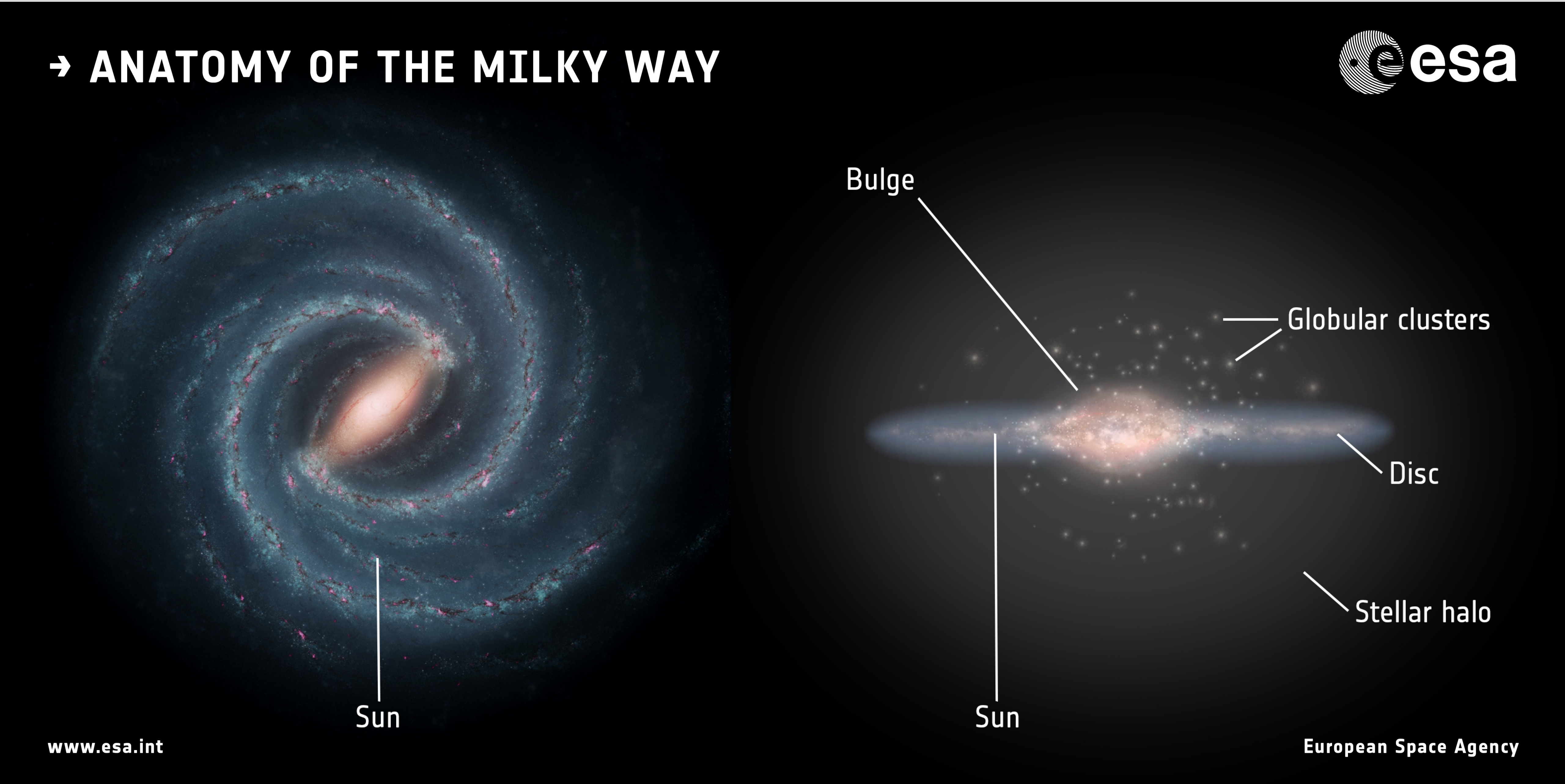
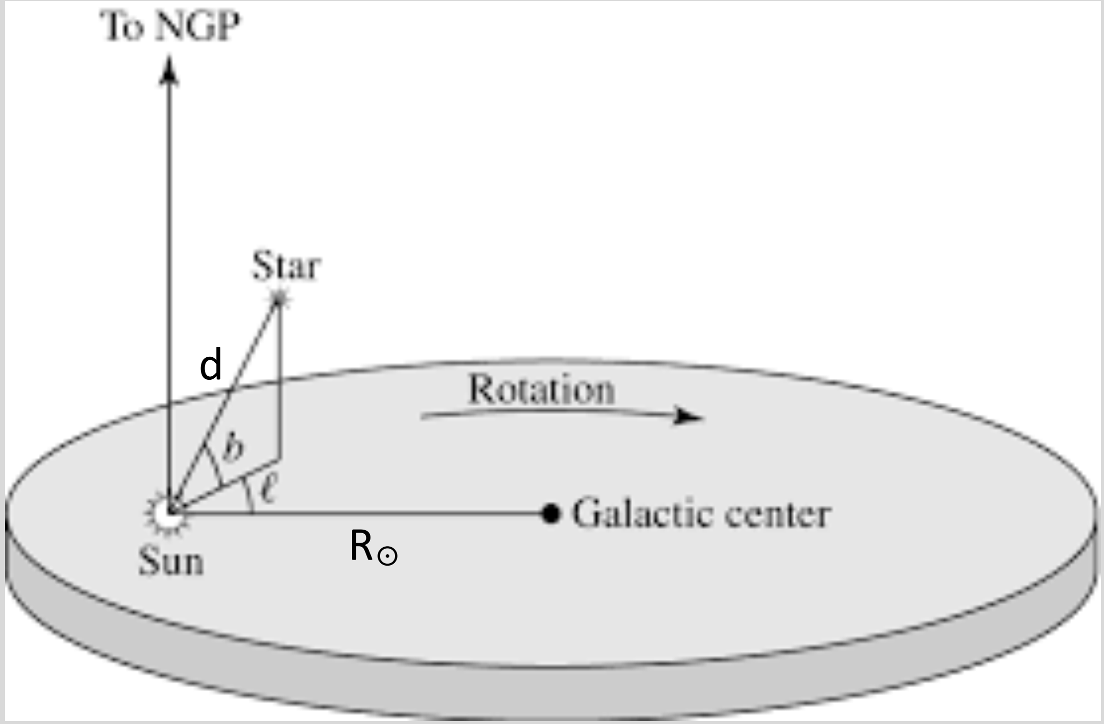
The Milky Way: A structural overview

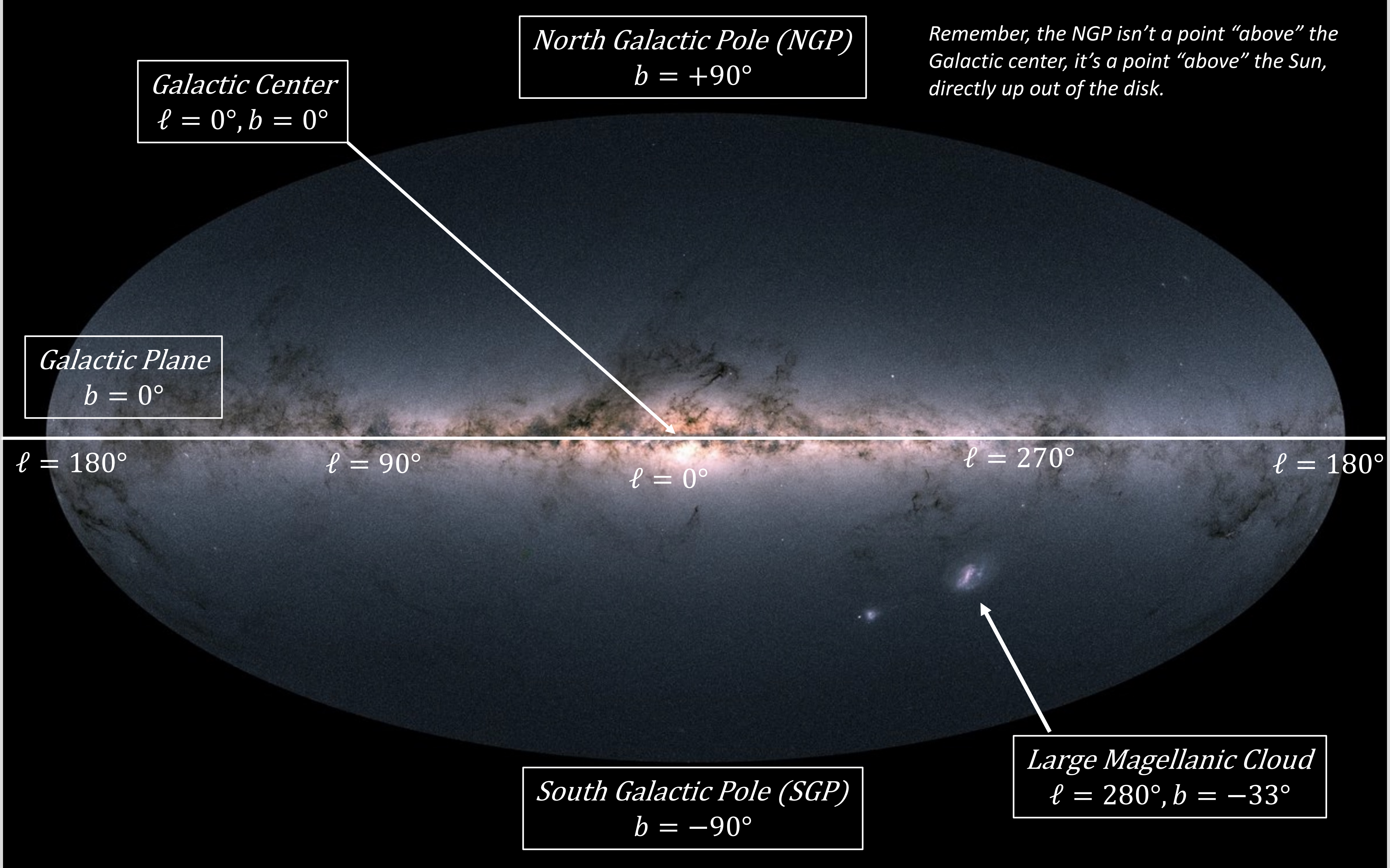


Galactic Coordinate Systems

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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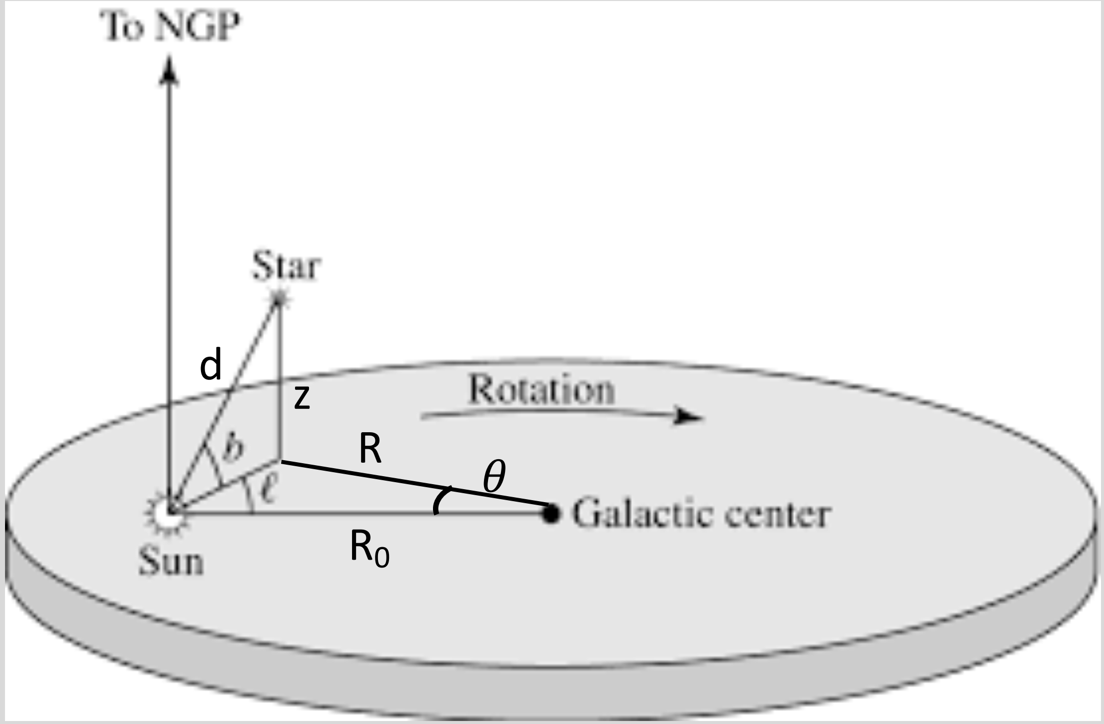
b : galactic latitude (above/below the plane)
(d : distance from Sun)

Physical cylindrical coordinates

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



Galactic Coordinate Systems

Galactic (angular) coordinates

ℓ : galactic longitude (0 = galactic center, 90 = direction of rotation)
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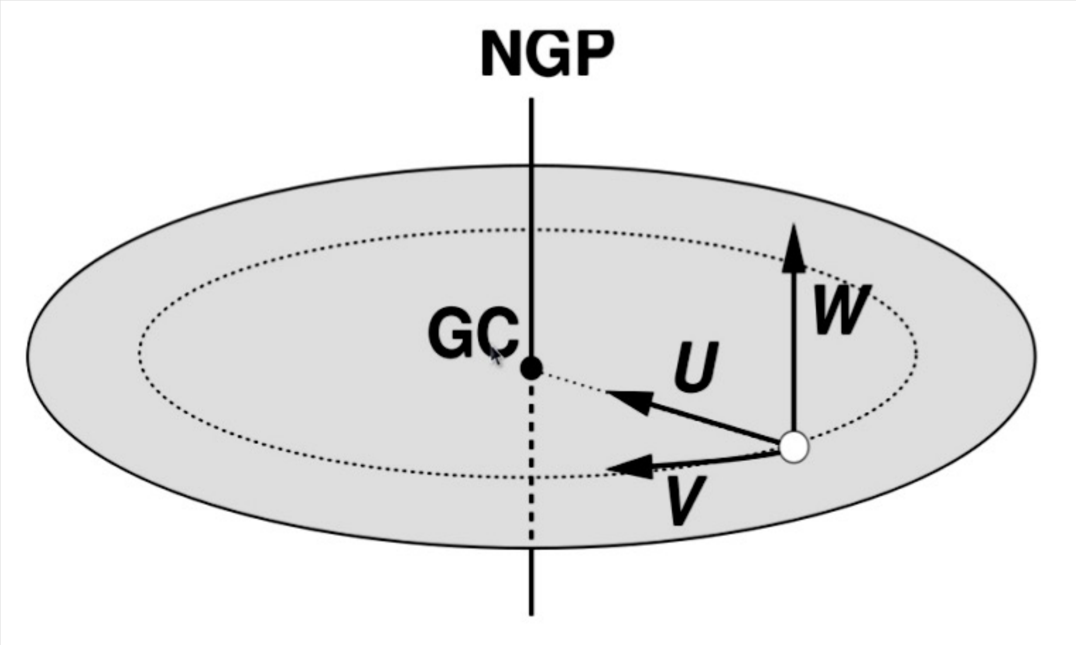
Physical cylindrical coordinates

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

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

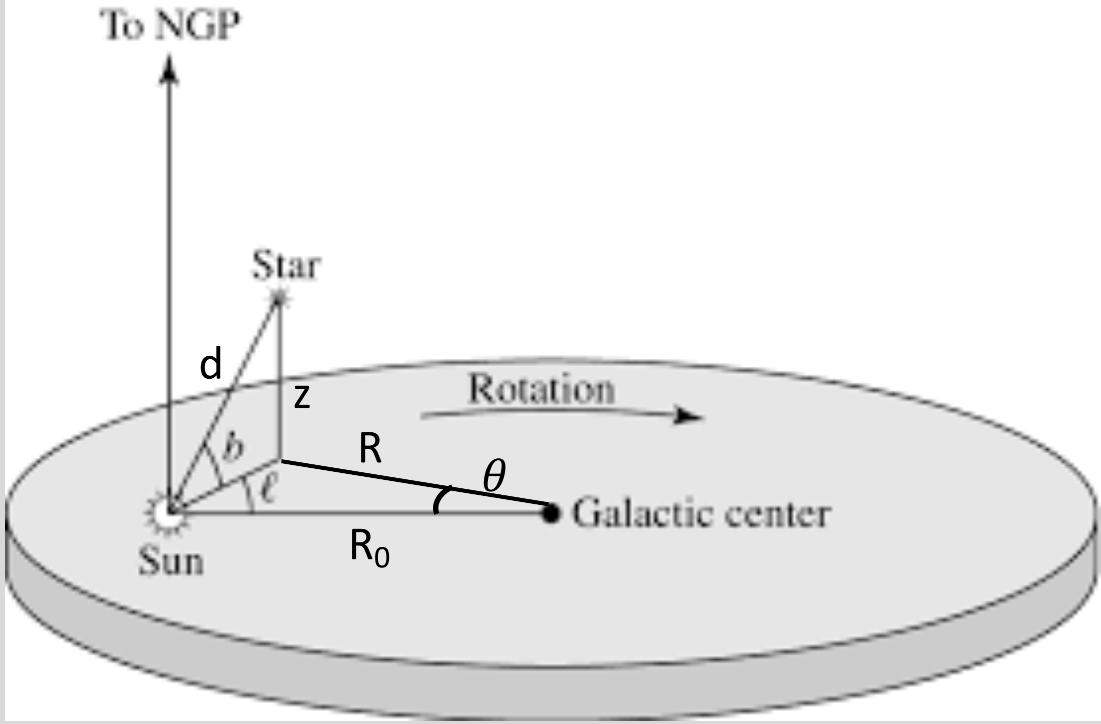
Imagine **a point at R_0 moving on a circular orbit** around the galactic center. This is called the **local standard of rest (LSR)**, and we want to measure the motion of stars with respect to this frame.

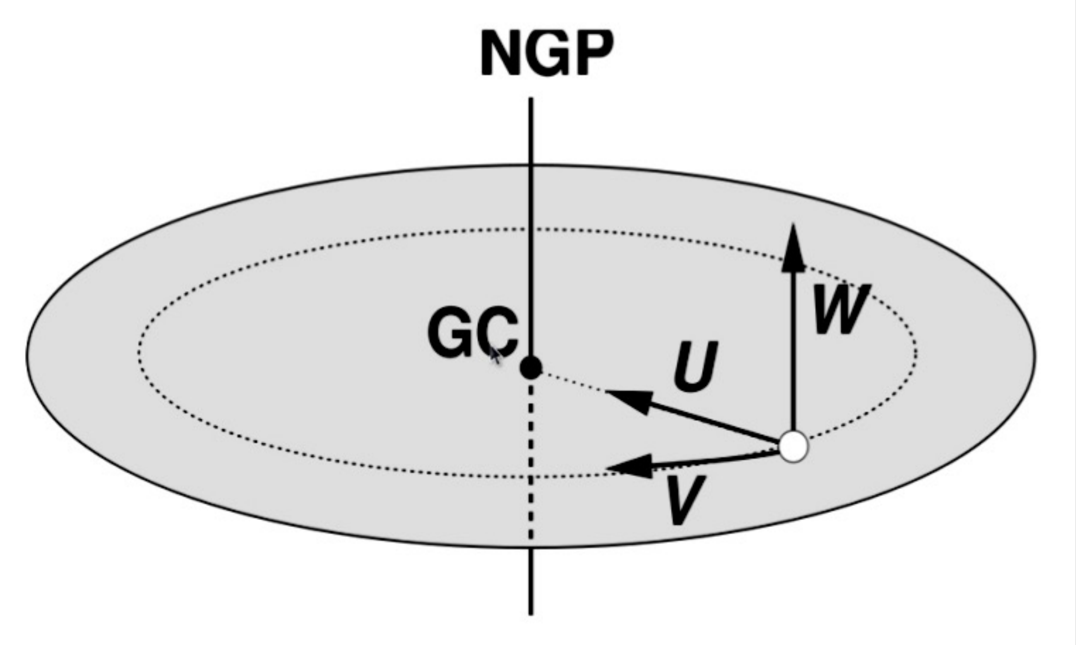
How do we measure the velocities of stars?

- 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": $(\sigma_U, \sigma_V, \sigma_W)$.

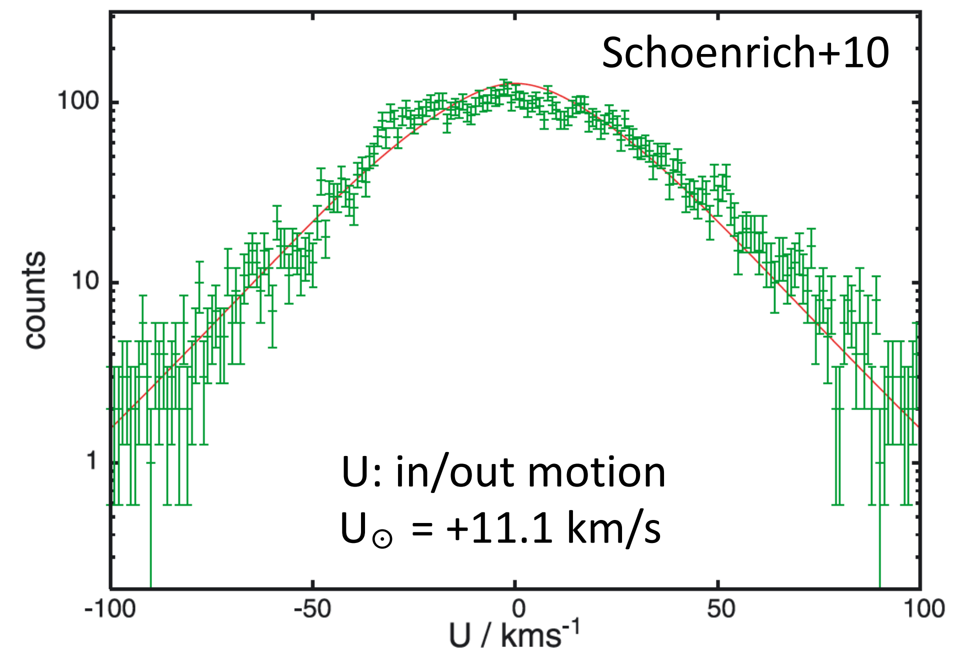
If, ***on average***, the local solar neighborhood moves with the LSR, nearby stars should have average $(\langle U\rangle, \langle V\rangle, \langle W\rangle) = (0,0,0)$.

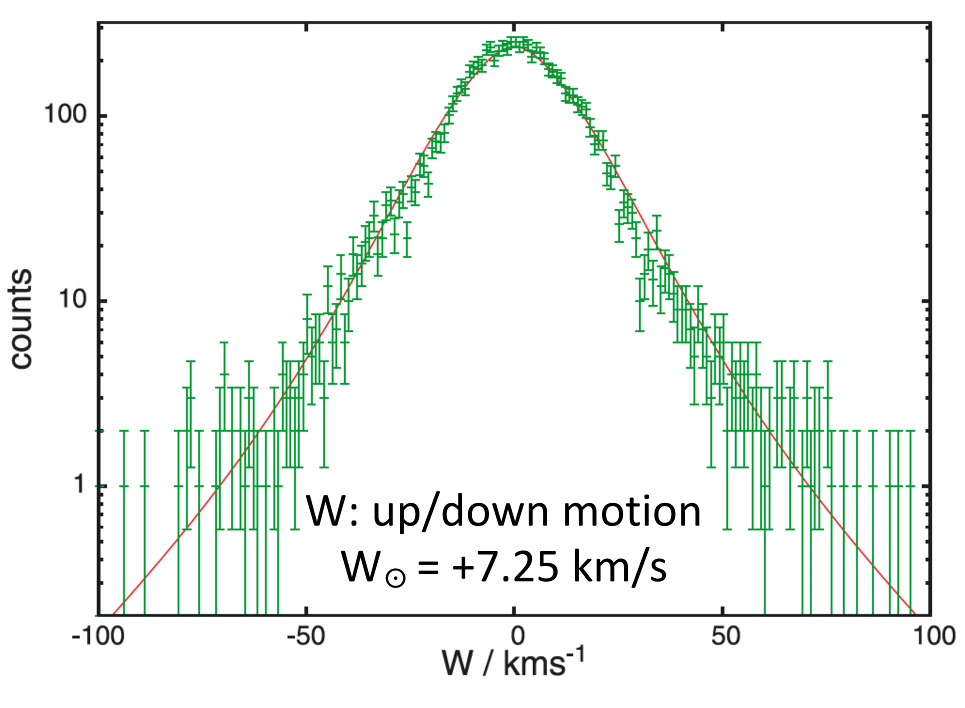
Measure velocity distributions, look for a non-zero mean velocity: this traces the Sun's motion.

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.



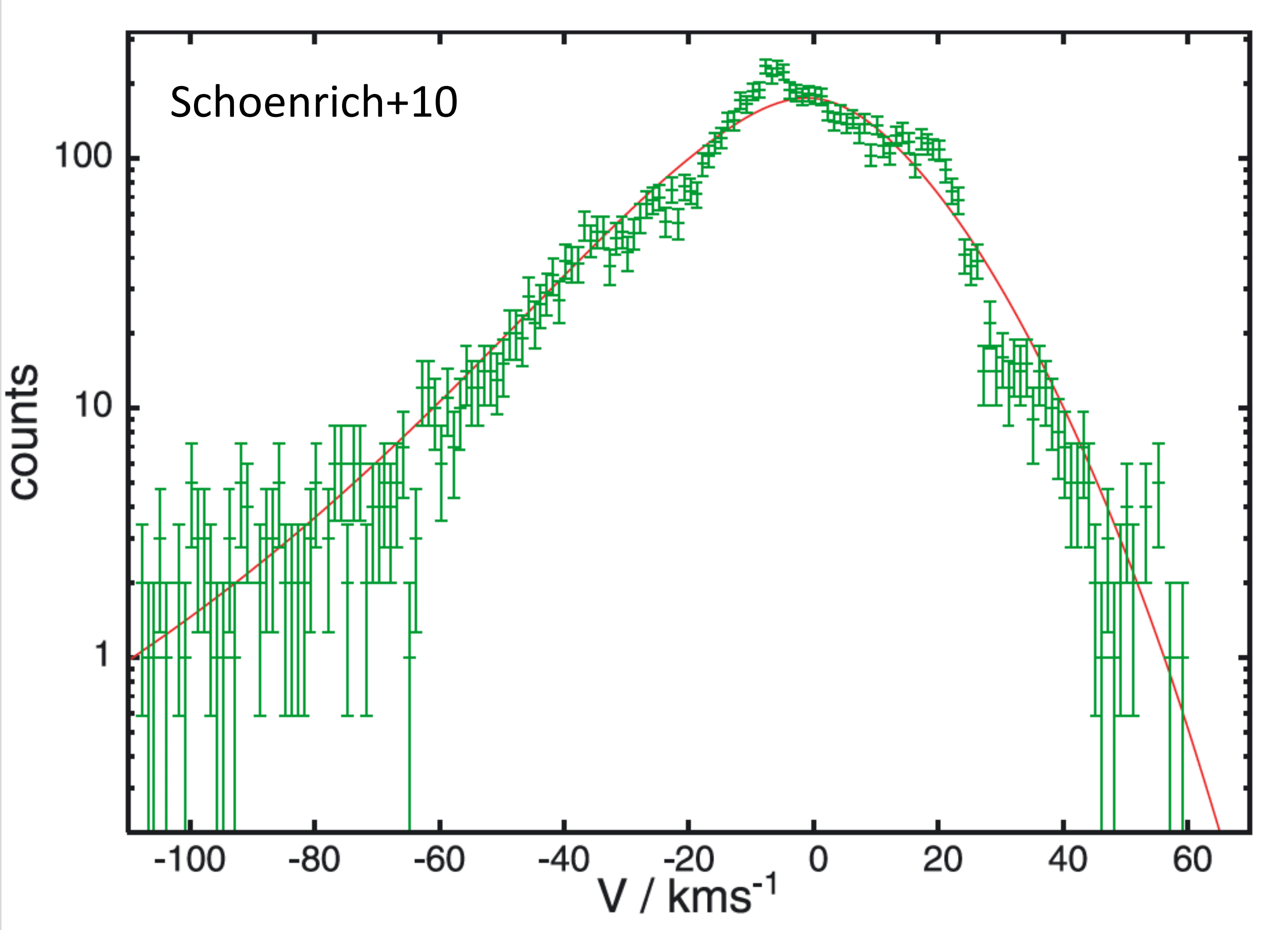


Measuring the Solar Motion: Asymmetric Drift

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:

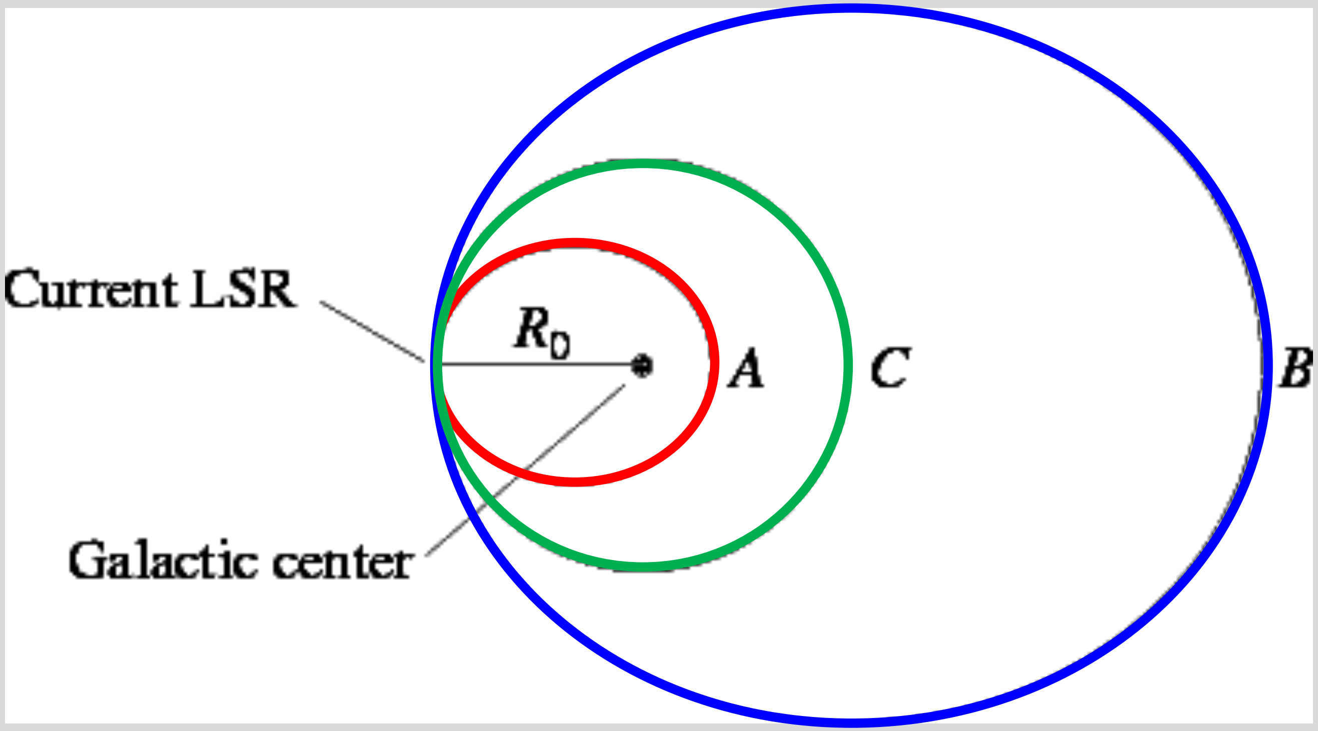
Elliptical orbit reaching R_0 at apocenter.
Stars move slowly at apo, so $v_\theta < v_{circ}$
This star lags the LSR ($V<0$)

Star B:

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

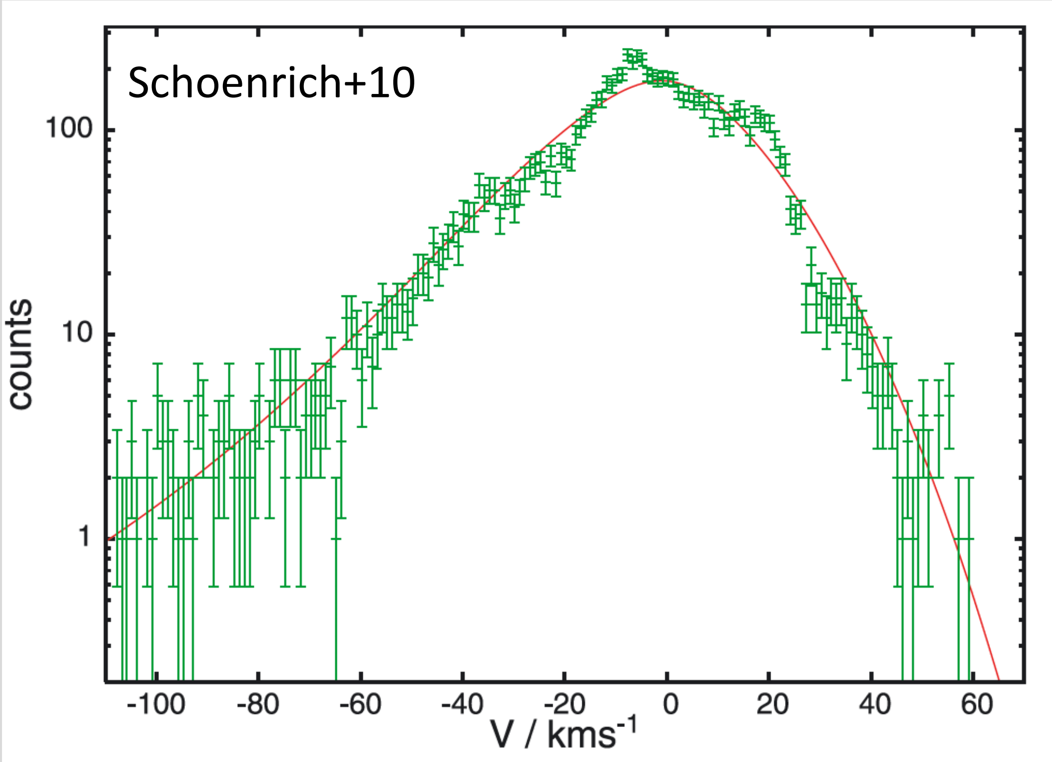
Star C:

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



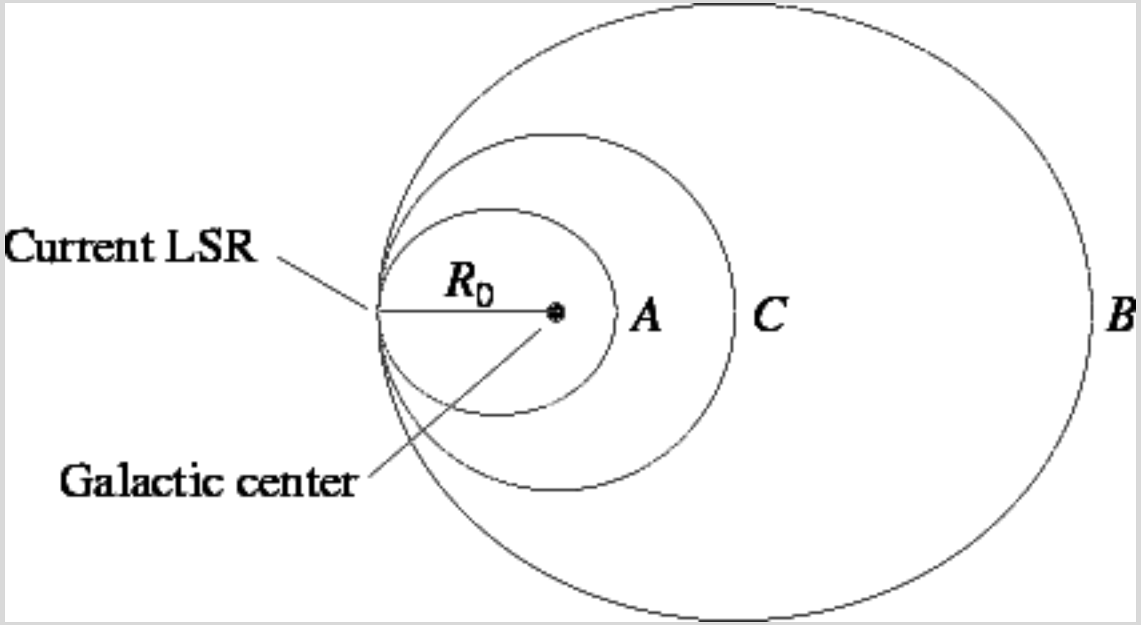
Measuring the Solar Motion: Asymmetric Drift

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?

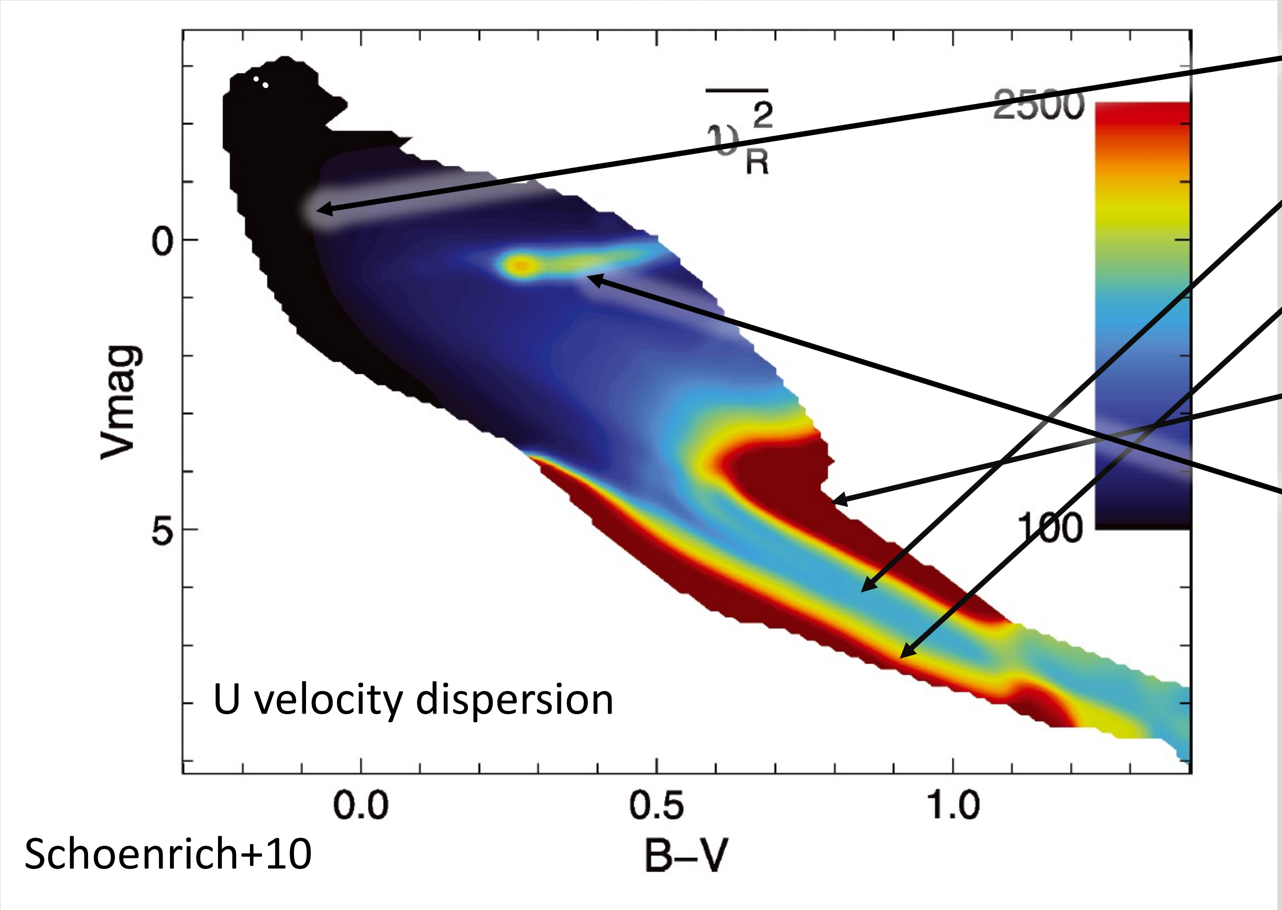
The density of stars is higher as you go inwards, so in the solar neighborhood there are more stars inside us coming out than outside is coming in. More laggers than leaders.

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

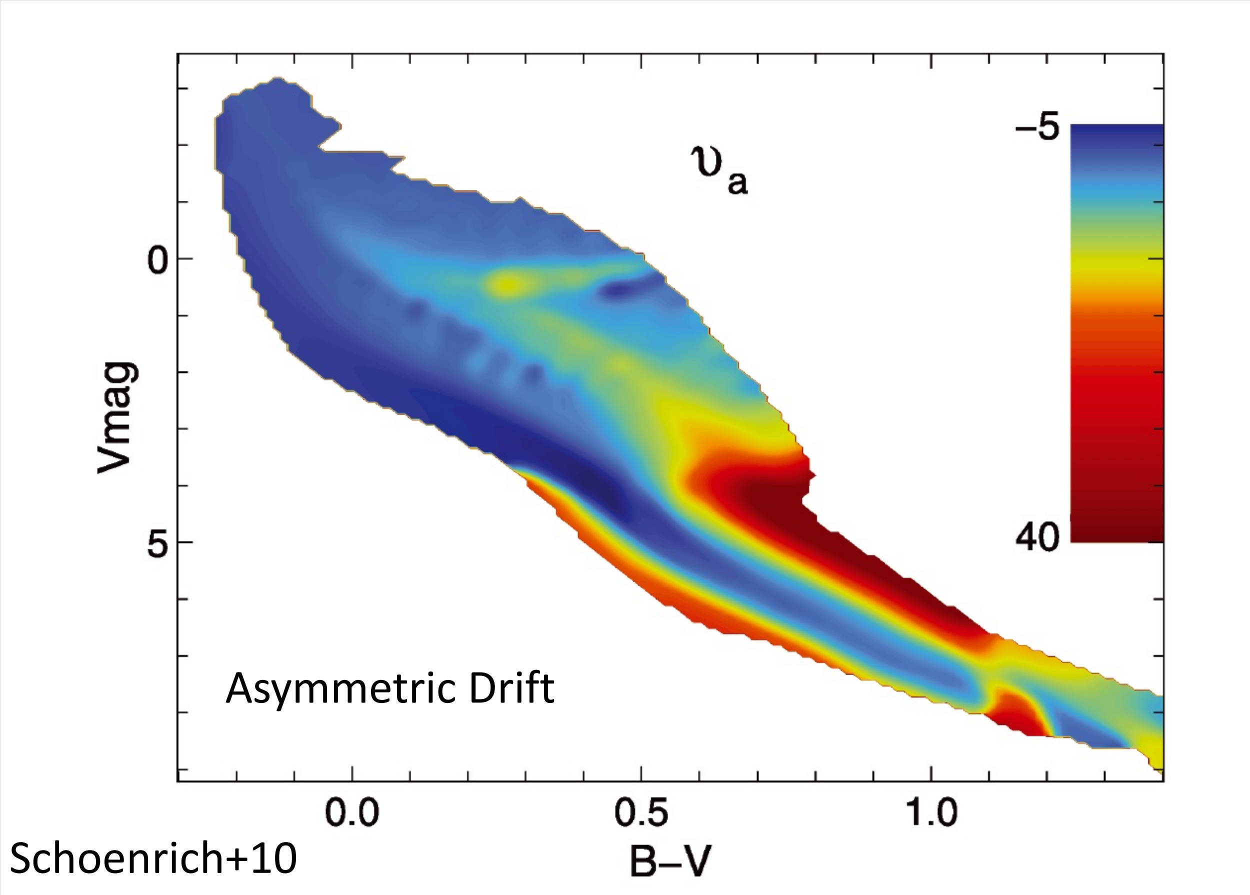
What is the common theme here? ***Mean stellar age.***

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”)



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.

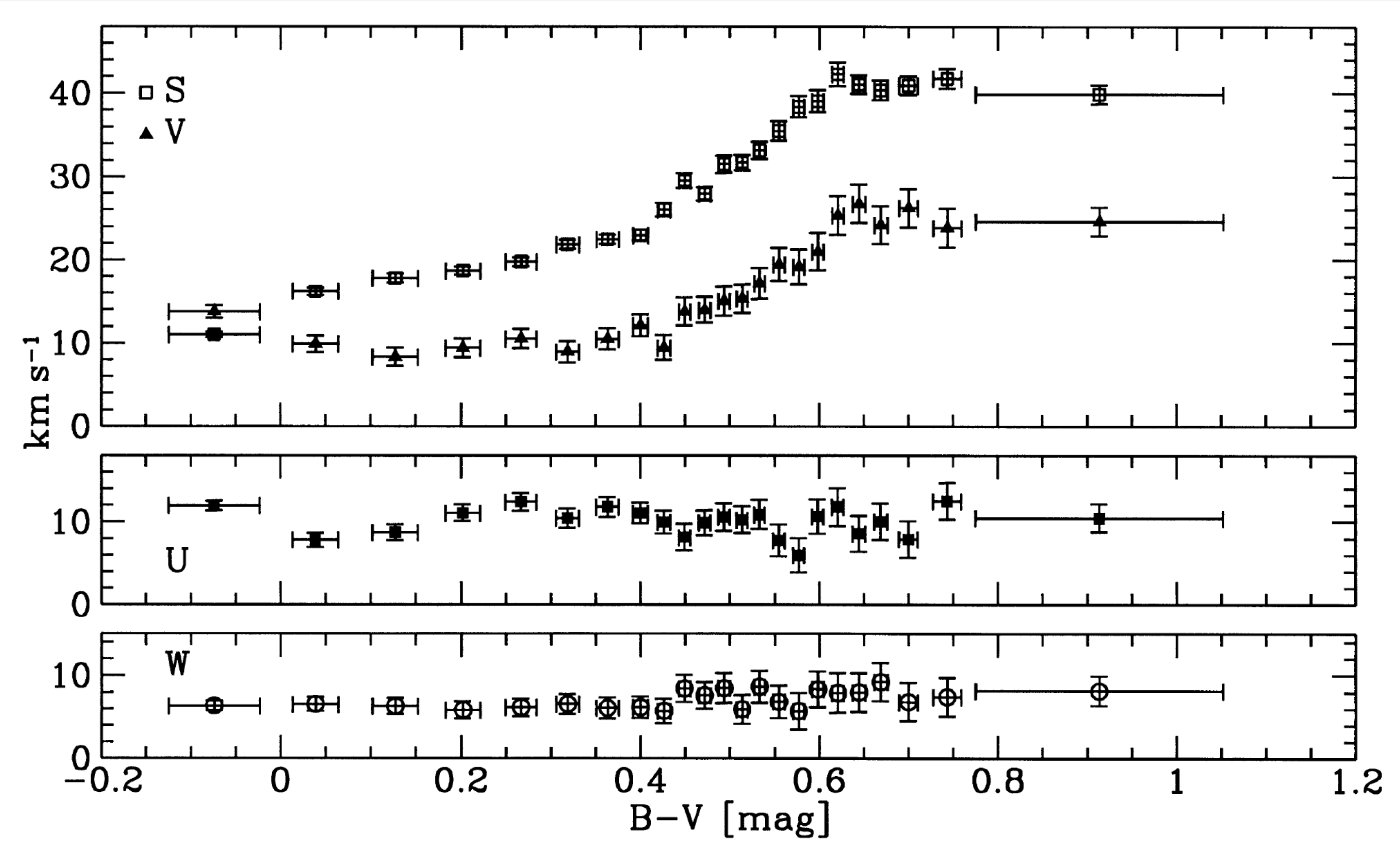
Measuring the Solar Motion: Effect of Asymmetric Drift

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

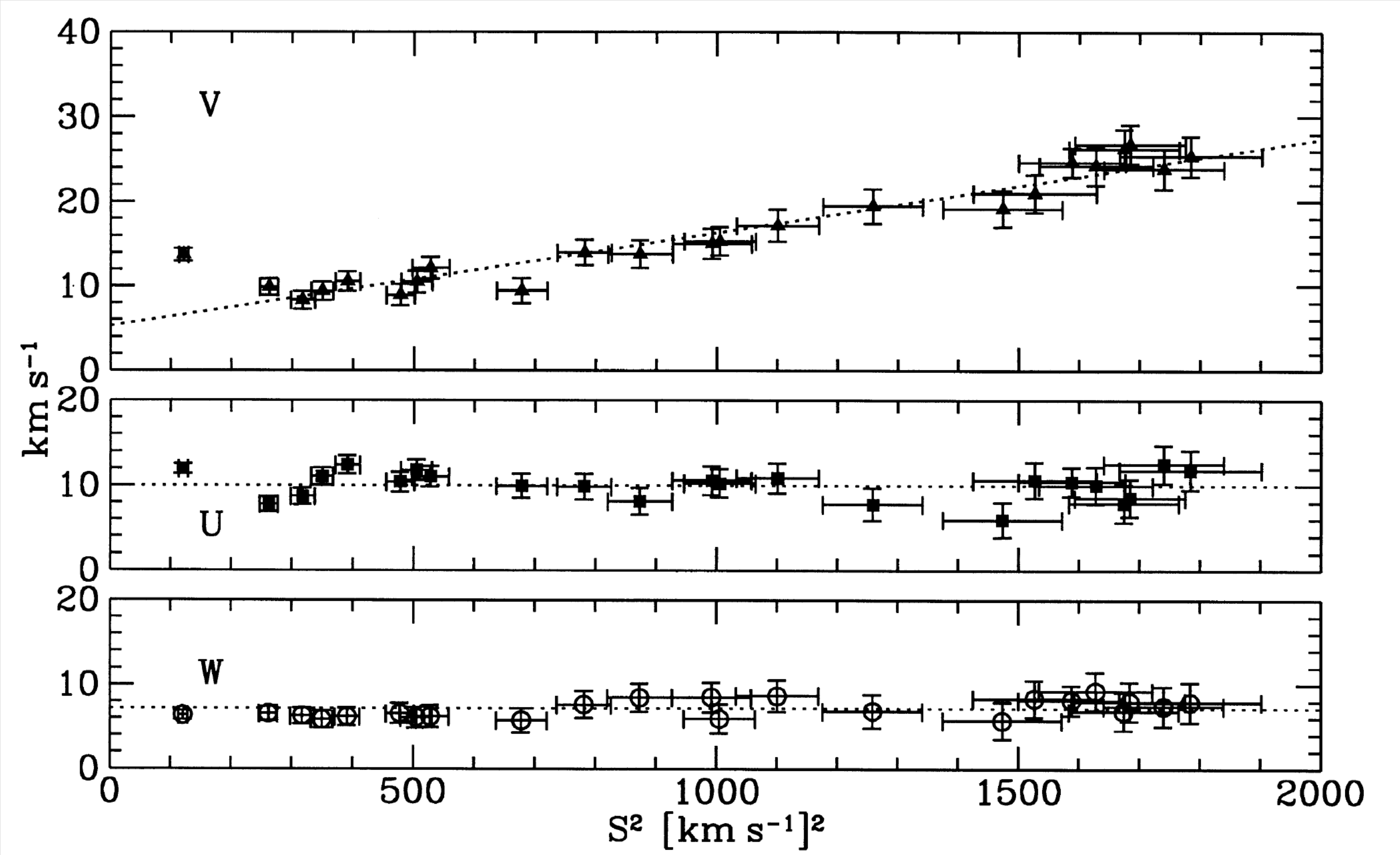
Define the solar motion with respect to a hypothetic population with zero velocity dispersion.

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**: $(\vec{x}, \vec{v})$

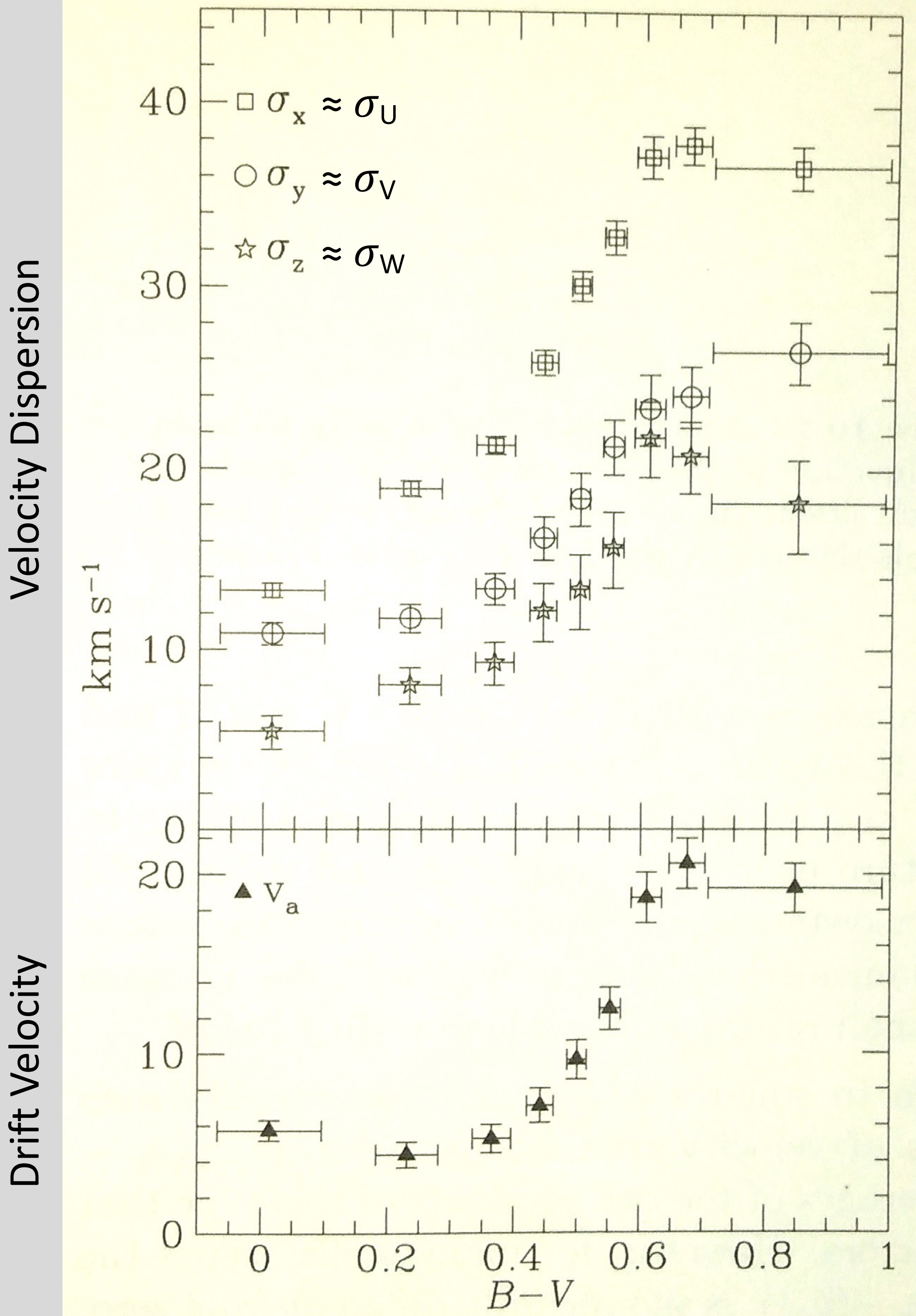
The kinematics of **stellar populations** in the solar neighborhood can be described using mean velocities and velocity dispersions (spread in velocities).

- 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.



Structure of the Milky Way Disk

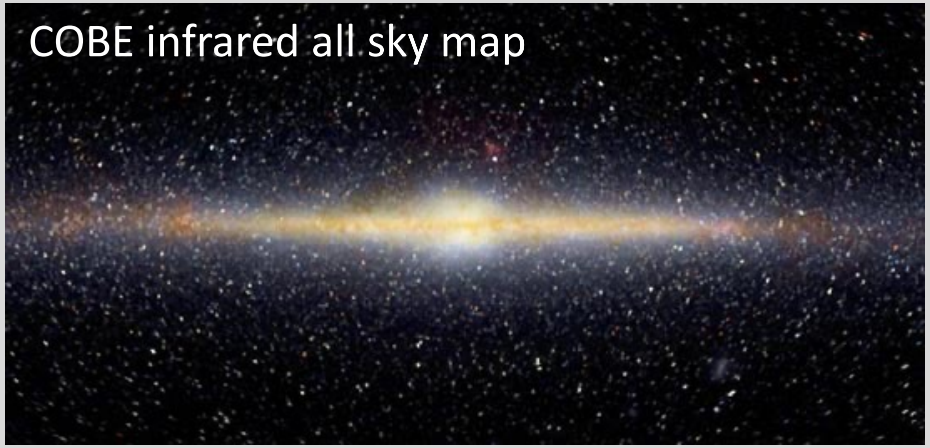
Density distribution roughly follows an exponential in R and z:

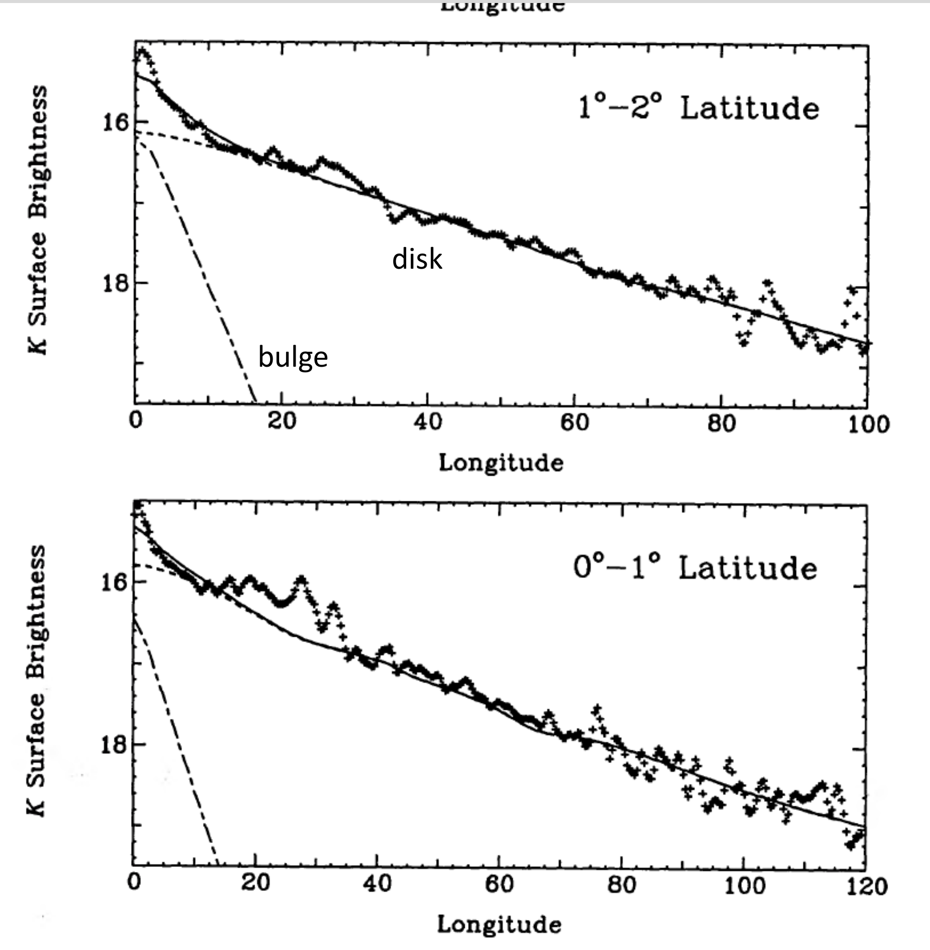
$$\rho(R,z) = \rho_0 e^{-R/h_R} e^{-|z|/h_z}$$

where h_R and h_z are the radial scale length and vertical scale height, respectively.

Radial scale length $h_R \approx$ 3 kpc (estimates range 2.5 – 3.5 kpc)

Vertical scale height h_z turns out to have a complex dependency on Galactic radius and stellar spectral type.





Spacelab K-band (near-IR) profiles (Kent+ 91)

Longitude essentially measures (angular) radius from galactic center.

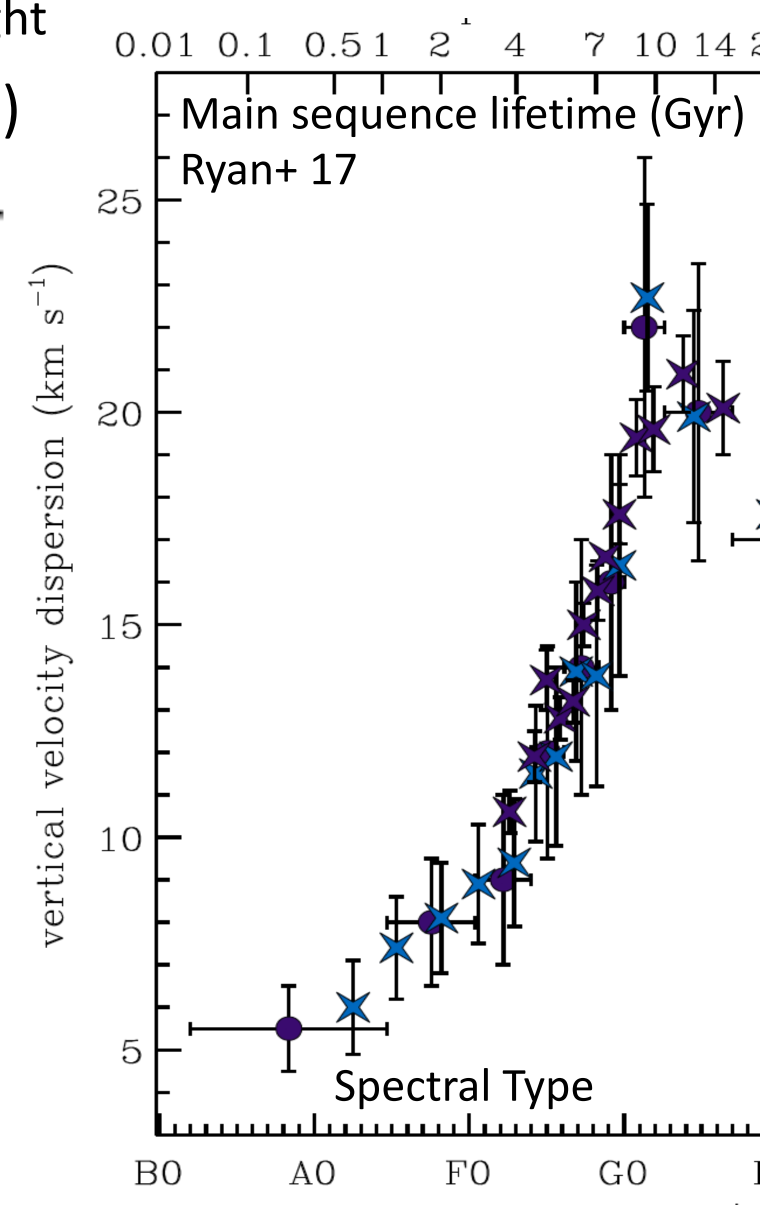
Scale Heights for different populations

What is this trend showing?

Why might we expect this?

Table 4-16. Scale Heights β_S in the Direction Perpendicular to the Galactic Plane and Surface Density Σ_S for Various Objects

Object	scale height h_z (pc)
O stars	50
Classical Cepheids	50
B stars	60
Galactic clusters	80
Interstellar dust and gas	120
A stars	120
F stars	190
Planetary nebulae	260
gK stars	270
Novae	300
dG stars	340
dK stars	350
dM stars	350
gG stars	400
White dwarfs	500



Vertical velocity dispersion: Why do we care?

Why would velocity dispersion and scale height correlate? Because of gravitational balance.

Think of a star oscillating up and down in the disk, held by the gravitation force of some mass *M*. We can balance kinetic and potential energy: $\frac{1}{2}m_* v_z^2 \cong \frac{GMm_*}{z}$ or, more simply: $v_z^2 \cong \frac{2GM}{z}$.

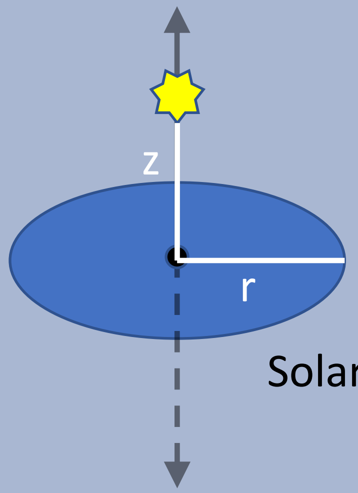
What is M? think of a patch of the disk with radius r and surface density Σ_0 (in $M_\odot/pc^2$). It will have a mass of $M = \Sigma_0 \pi r^2$.

If $r \approx z$, we can put that in for M and get $v^2 \cong 2\pi G \Sigma_0 z$

Now consider of a group of stars. Replace individual values (v^2, z) with ensemble values (σ_W^2, h_z) to get: $\sigma_W^2 \sim 2\pi G \Sigma_0 h_z$

This is known as the **Oort Limit**, and can be used to estimate the total mass density of the Galactic disk in the solar neighborhood.

Current estimates come in at $\Sigma_0 \approx 70\ M_\odot/pc^2$ or so.



Solar neighborhood

Galactic disk

Disk Stars: Metallicity

Stars in the solar neighborhood show a spread of metallicity.

Notes:

- [Me/H]: metallicity
- The Sun is slightly on the high end of the distribution
- The distribution is asymmetric, with a tail to low metallicities.

Nordstrom+ 04

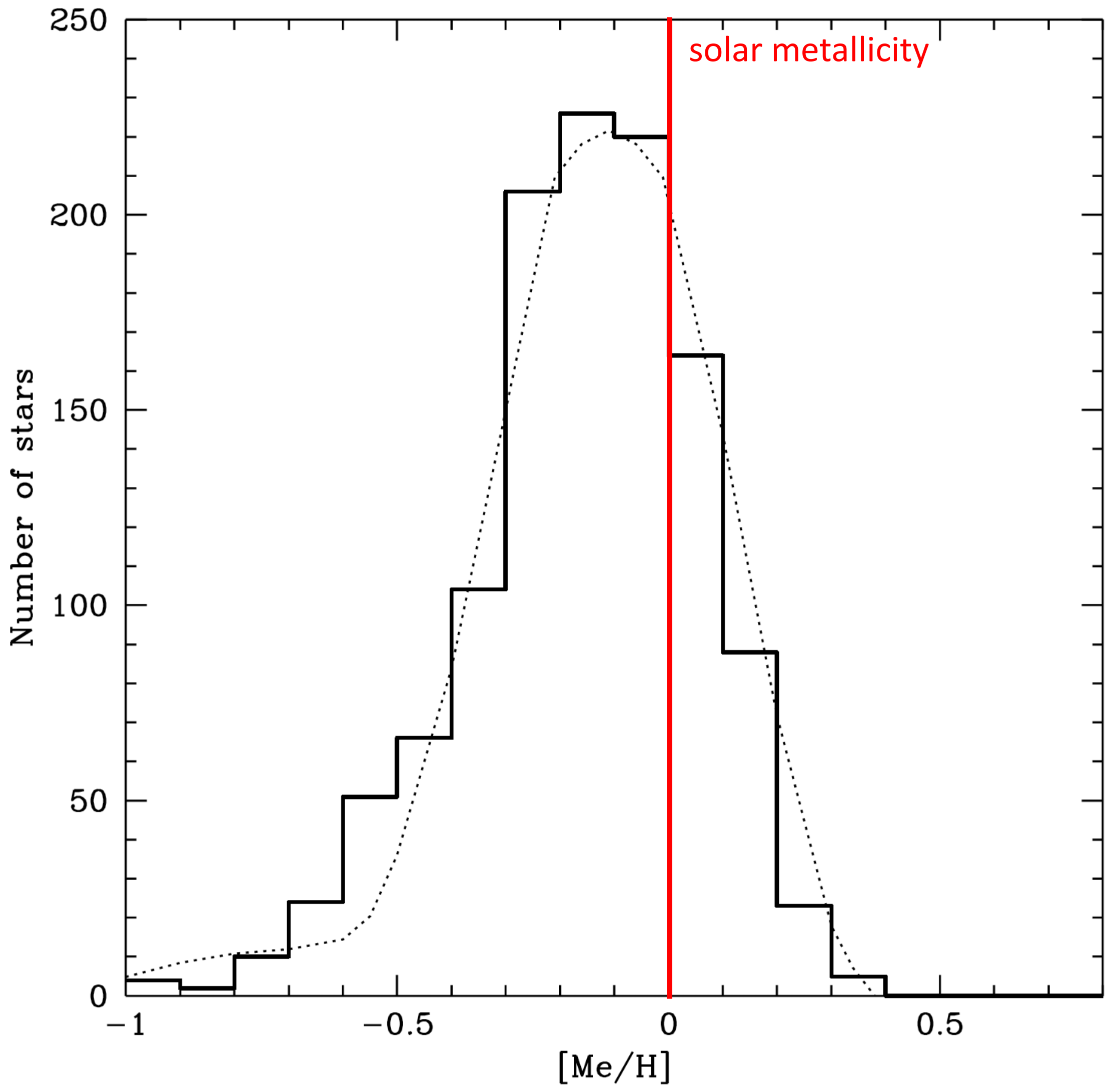


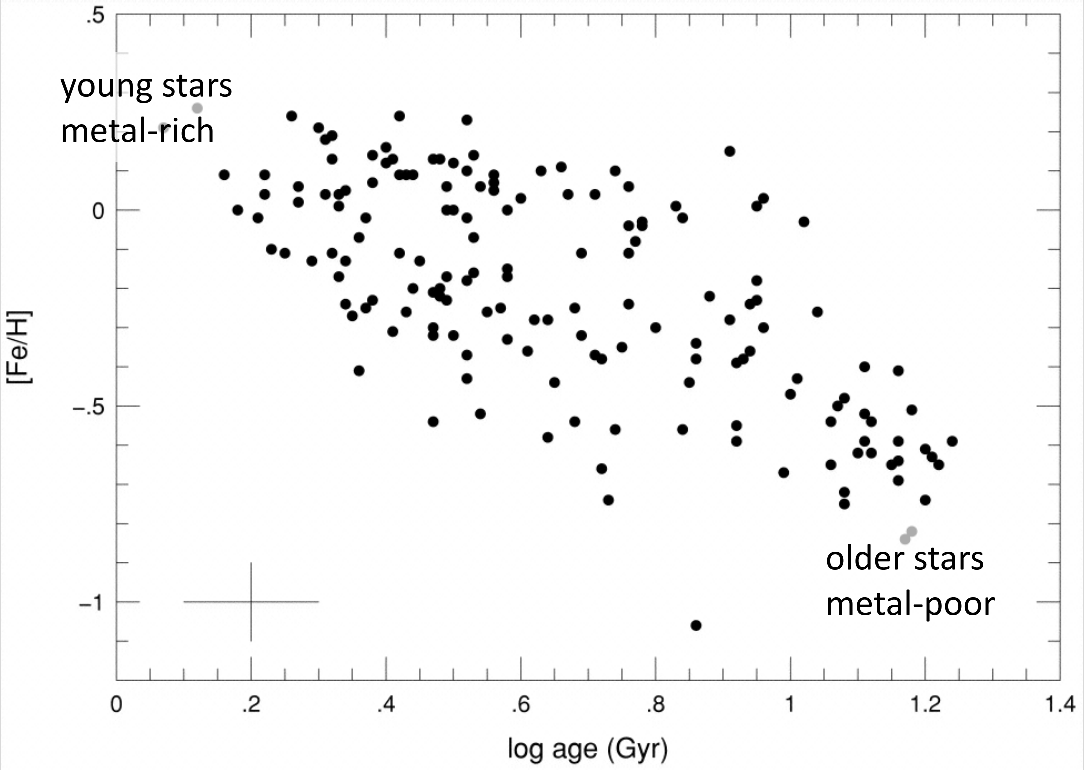
Fig. 26. Distribution of metallicities for the volume complete sample of single stars (full histogram). For comparison the dotted curve shows the reconstructed distribution for G dwarfs from Jørgensen (2000), which is corrected for scale height effects and measurement errors.

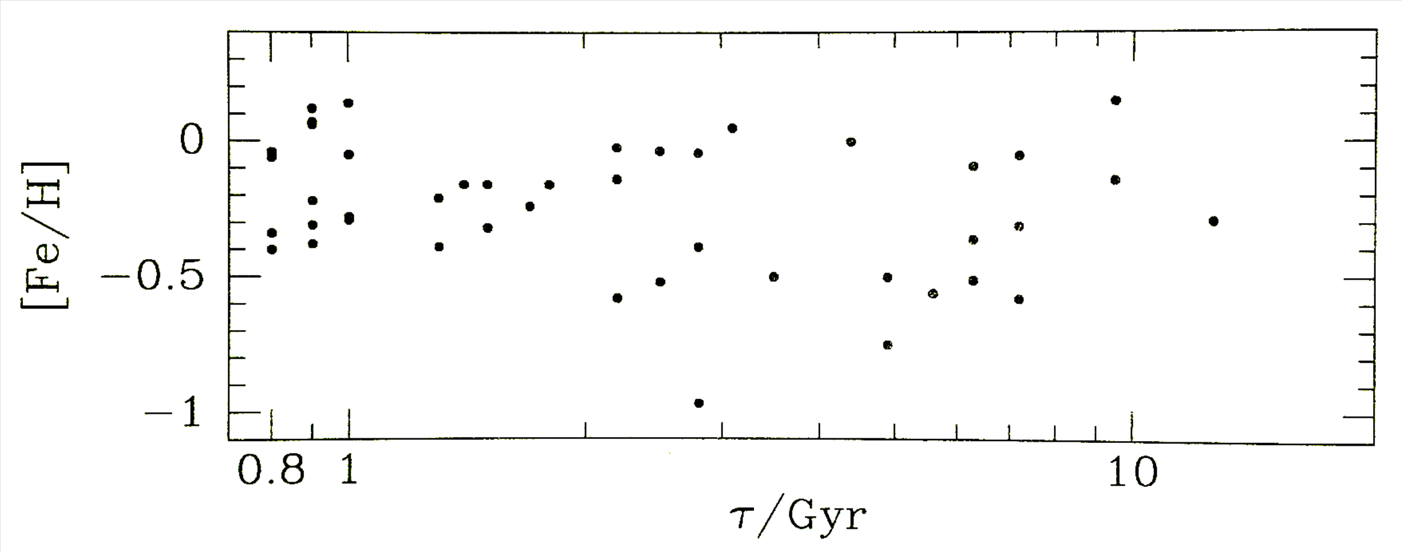
Disk Stars: Age – Metallicity Relationship

Age metallicity relationship (AMR) shows a lot of scatter. Some studies suggest a trend, others do not.

Individual Stars
Garnett & Kobulnicky 00, updating Edvardsson+ 93

Old open star clusters
Binney & Merrifield Fig 10.23



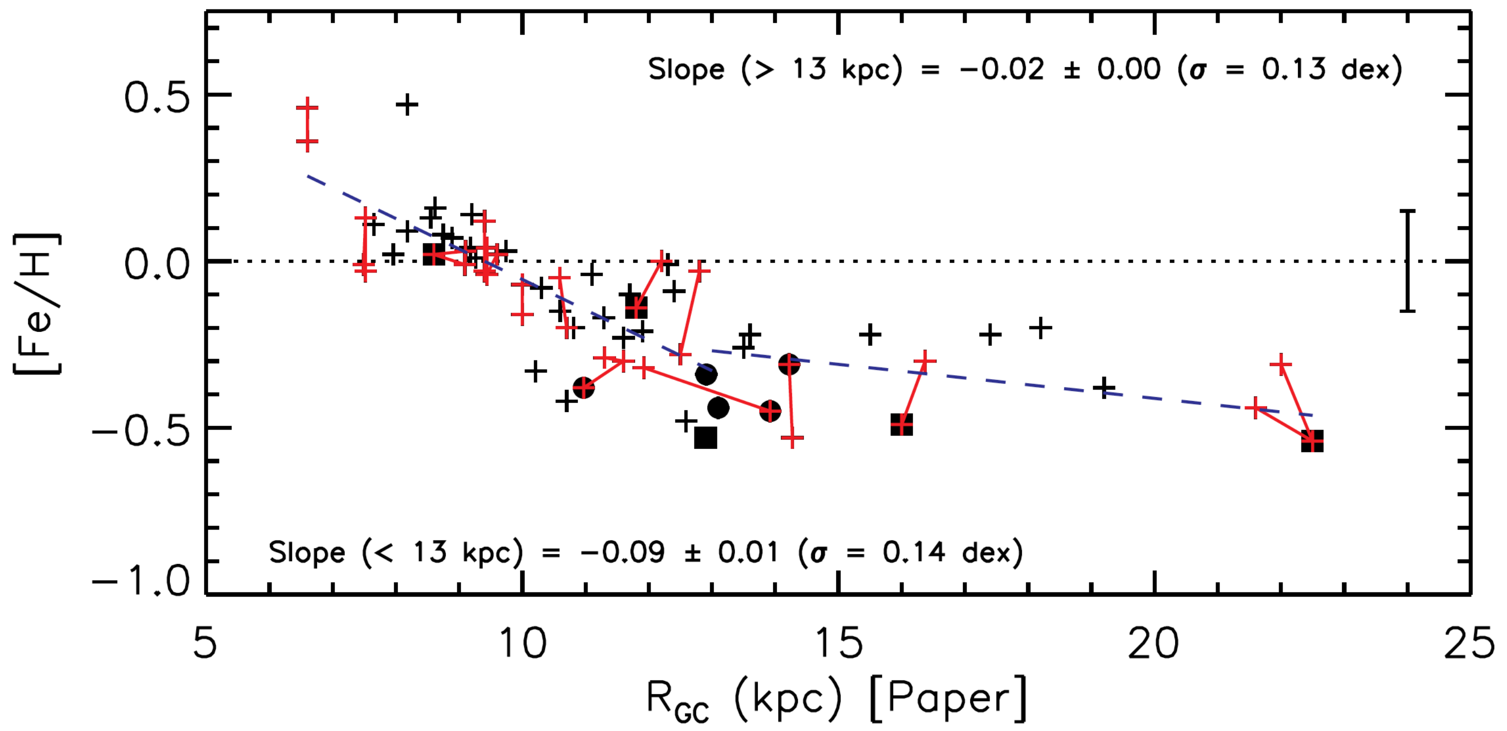


Again, the age-metallicity relationship has a lot of scatter. There are old stars with high metallicity and younger stars with low metallicity.

Disk Stars: Radial Metallicity Gradient

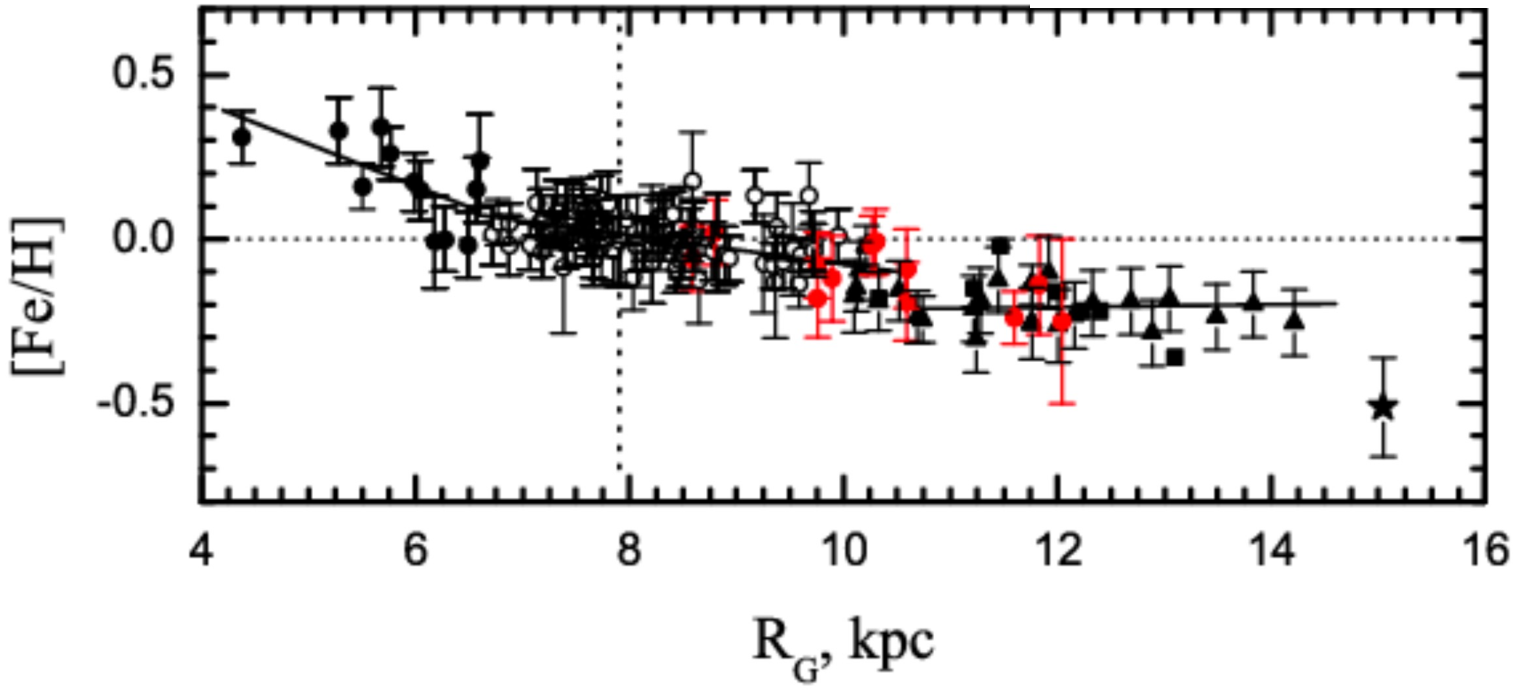
The mean metallicity of the Galaxy's disk declines as a function of radius.

Outer disk is metal poor compared to the inner disk.



Gradient from Cepheids

Andrievsky+ 04



Gradient from Open Clusters

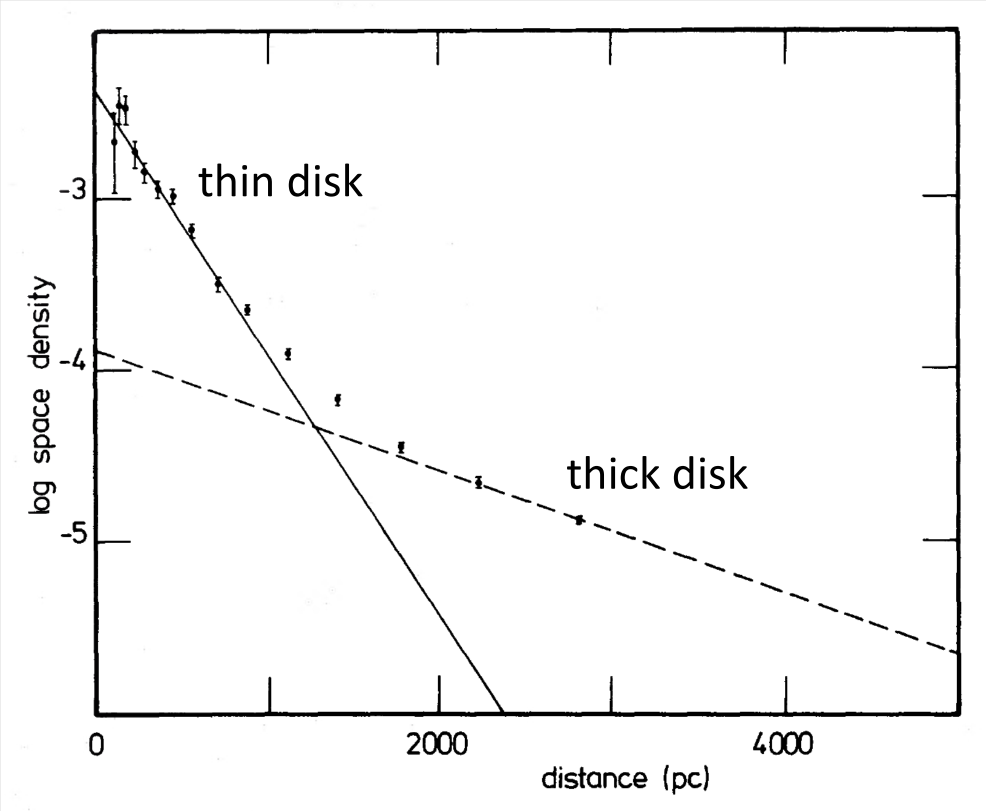
Yong+ 12

Thin and Thick Disk

Scale height can be better fitted as a combination of two exponentials:

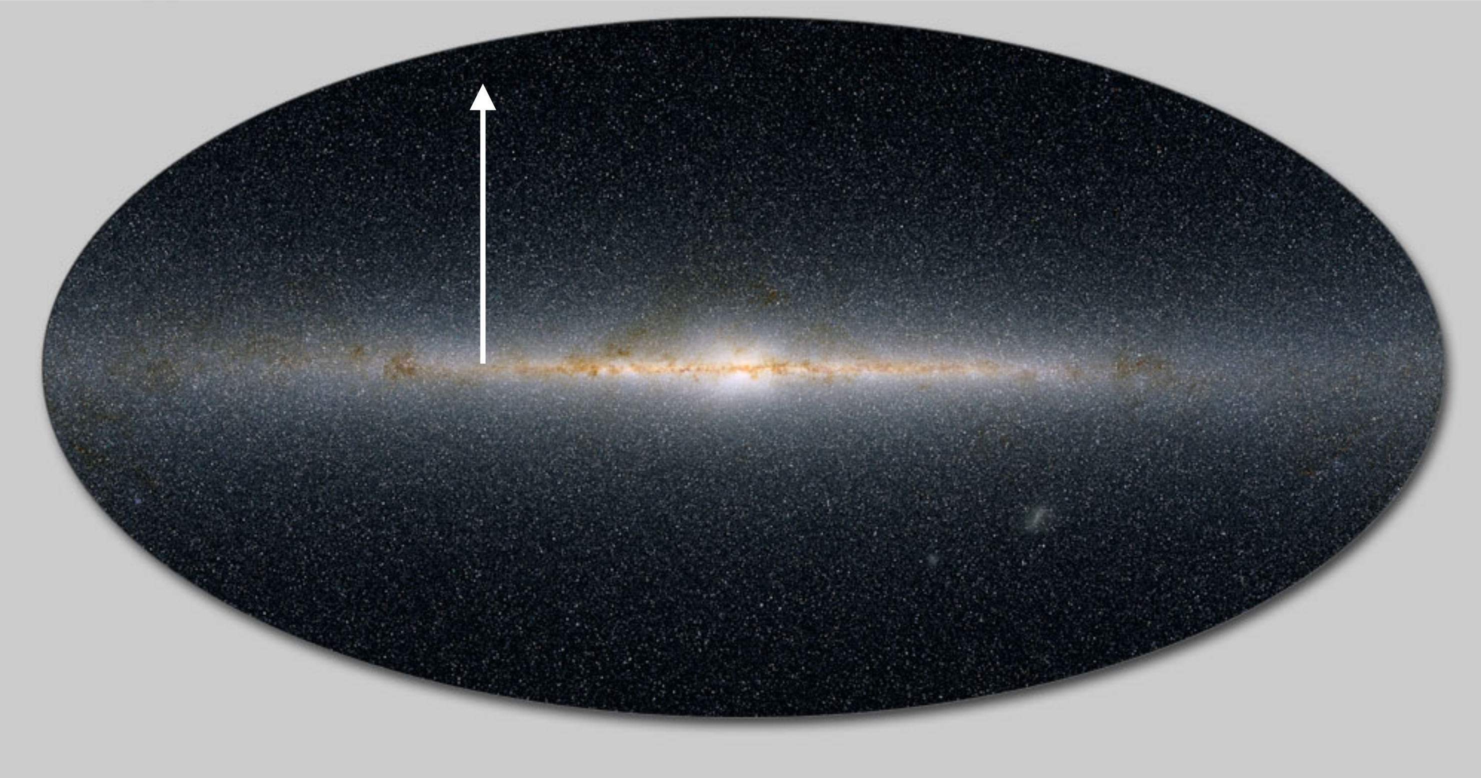
- Thin disk: $h_z \approx 300$ pc
- Thick disk: $h_z \approx 1$ kpc

Gilmore & Reid 1983



vertical height from midplane

2MASS near-IR map



Thick Disk

The thick disk is thicker but more centrally concentrated than the thin disk.

It is kinematically hotter than the thin disk.

It is older and more metal-poor than the thin disk.

	Thin Disk	Thick Disk
Scale height (h_z)	300 pc	1 kpc
Scale length (h_R)	3–4 kpc	2 kpc
$(\sigma_U, \sigma_V, \sigma_W, v_a)$ Kinematics	≈ (30, 20, 20, 15) km/s	≈ (60, 40, 40, 30) km/s
Stellar pops	Mix of stellar ages, more metal-rich stars	Old stars, somewhat more metal-poor

Total luminosity of thick disk ≈ 10% that of the thin disk

Edvardsson+ 93

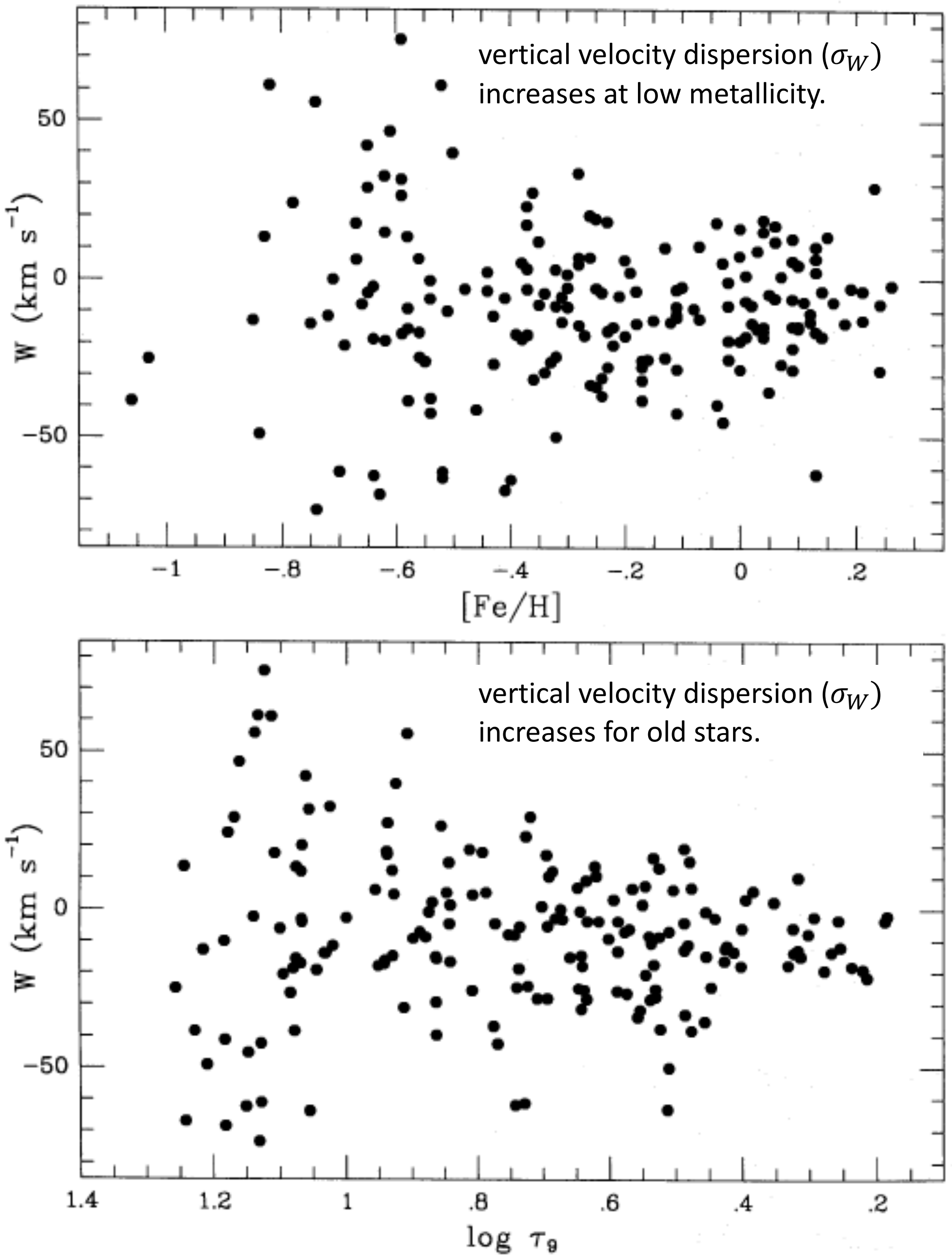


Fig. 16a and b. Stellar velocities perpendicular to the galactic plane, W, vs iron abundance **a** and age **b**, τ_9 is the age in 10^9 years

Metallicity structure of the thin and thick disk

Hayden+15

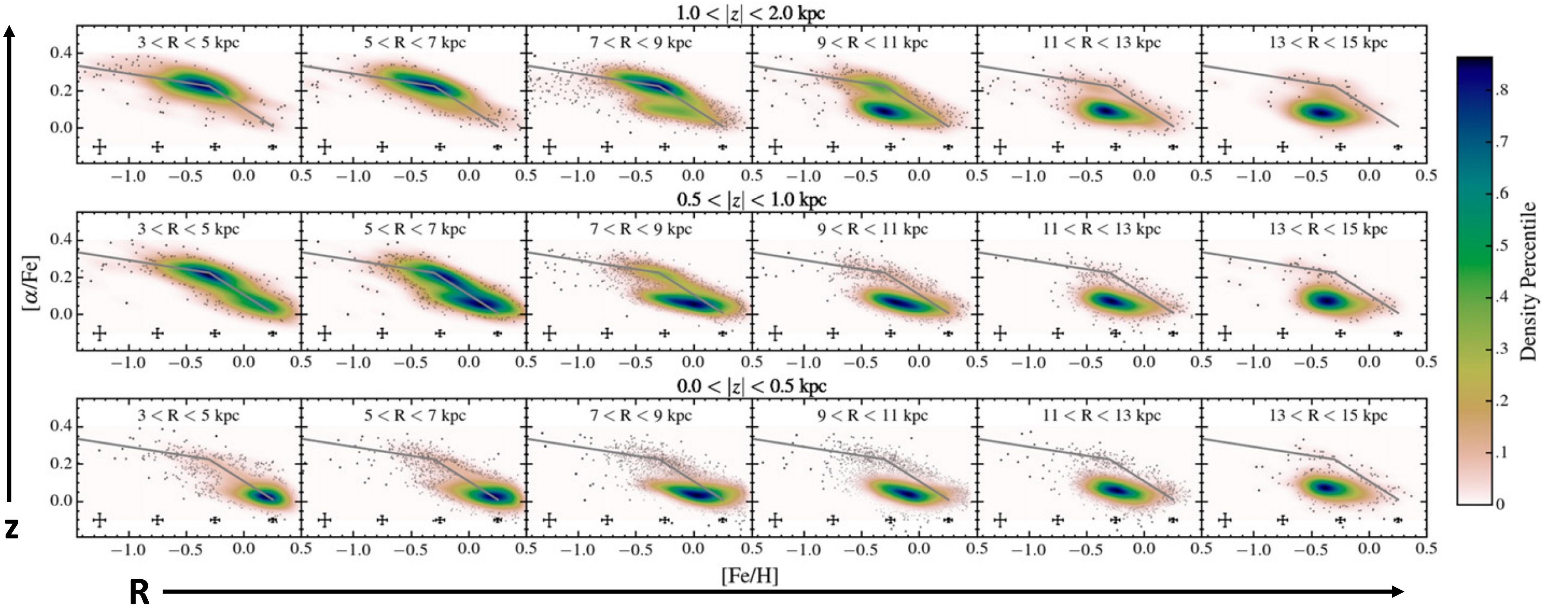


Figure 4. Stellar distribution of stars in the [α/Fe] vs. [Fe/H] plane as a function of R and $|z|$. The typical uncertainty in the abundances is shown as a function of metallicity across the bottom of each panel. The size of individual points is inversely related to the density at that location, to avoid saturation. Top: observed [α/Fe] vs. [Fe/H] distribution for stars with $1.0 < |z| < 2.0$ kpc. Middle: observed [α/Fe] vs. [Fe/H] distribution for stars with $0.5 < |z| < 1.0$ kpc. Bottom: observed [α/Fe] vs. [Fe/H] distribution for stars with $0.0 < |z| < 0.5$ kpc. The gray line on each panel is the same, showing the similarity of the shape of the high-[α/Fe] sequence with R. The extended solar-[α/Fe] sequence observed in the solar neighborhood is not present in the inner disk ($R < 5$ kpc), where a single sequence starting at high [α/Fe] and low metallicity and ending at solar [α/Fe] and high metallicity fits our observations. In the outer disk ($R > 11$ kpc), there are very few high-[α/Fe] stars.

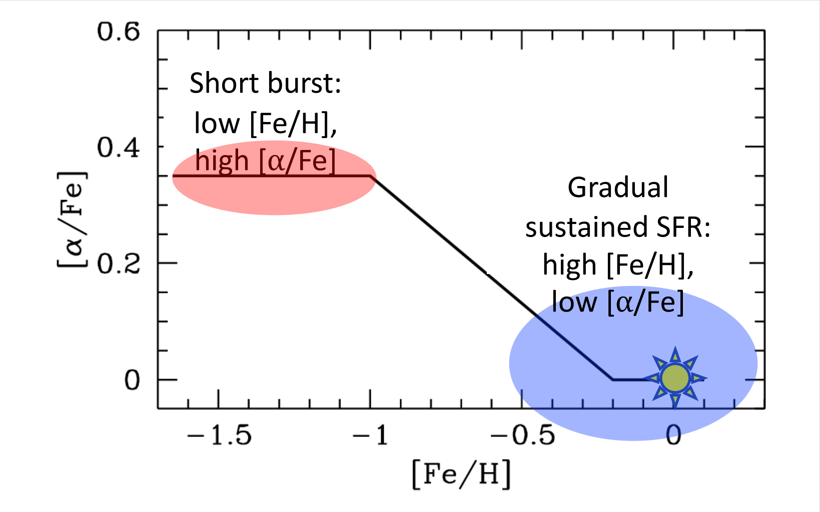
Metallicity structure of the thin and thick disk

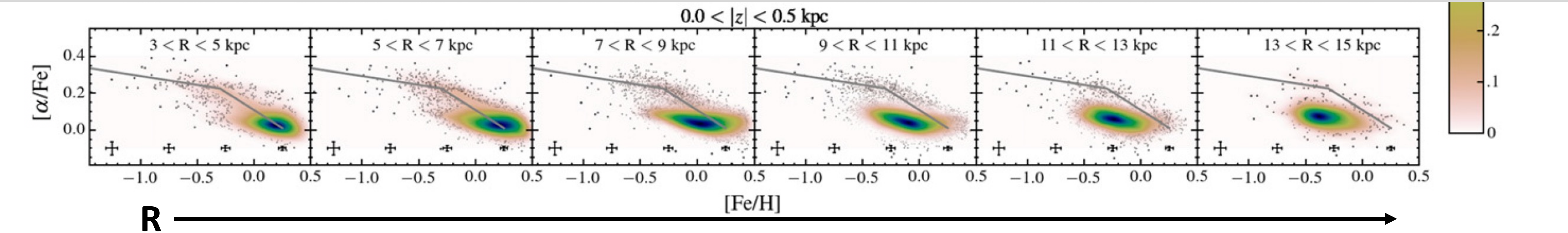
Look at radial metallicity trends for stars in the disk plane.

As radius increases, [Fe/H] decreases, but stars remain relatively solar in [α/Fe].

This is a sign of slow “inside-out” formation of the thin disk. Star formation and chemical evolution may have been going on longer in the inner disk, but overall everything has been built-up slowly over time.

Remember how [α/Fe] and [Fe/H] track star formation and enrichment history.

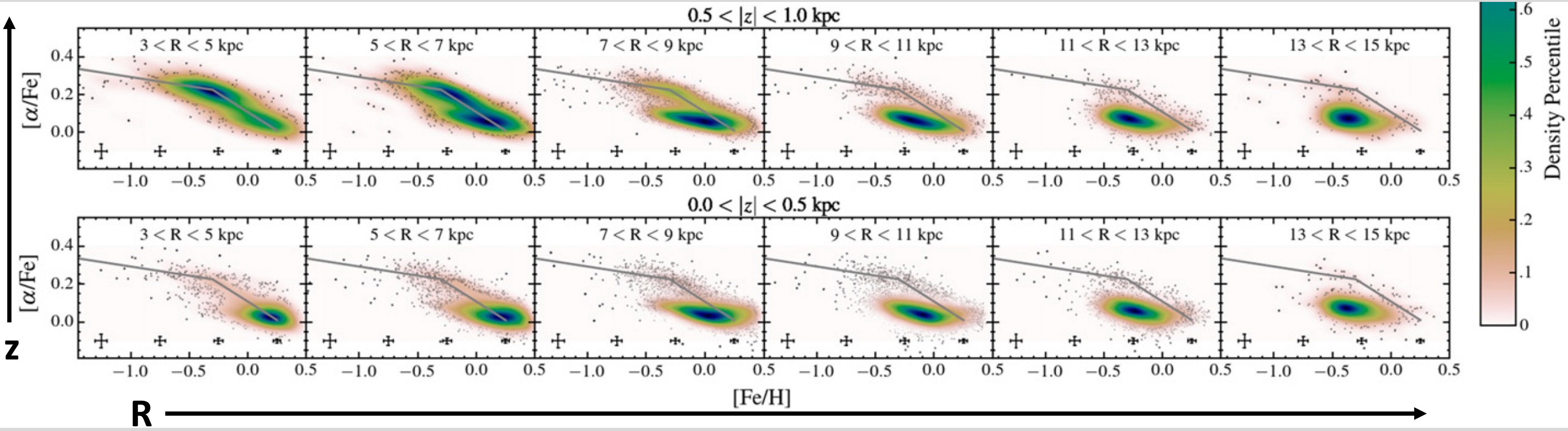




Metallicity structure of the thin and thick disk

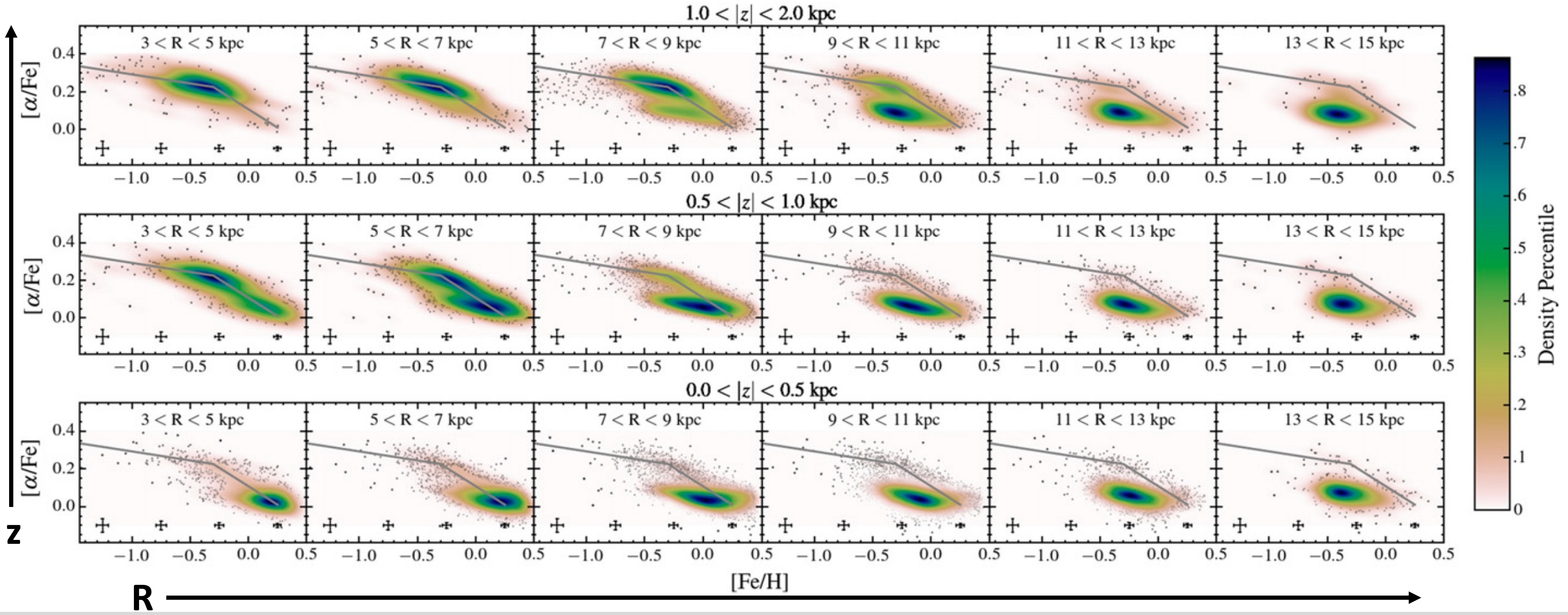
Now compare to stars over the same radial range, but higher up in height (z).

Inner parts look very different – lower metallicity and strong α-enhancement. But only the inner parts. Outer parts still look “normal”. This is the signature of the thick disk -- built up earlier and faster than the thin disk, but also not as radially extended.



This argues that the thick disk is not just scattered thin disk stars, or else the thick disk would have the same metallicity pattern as the thin disk.

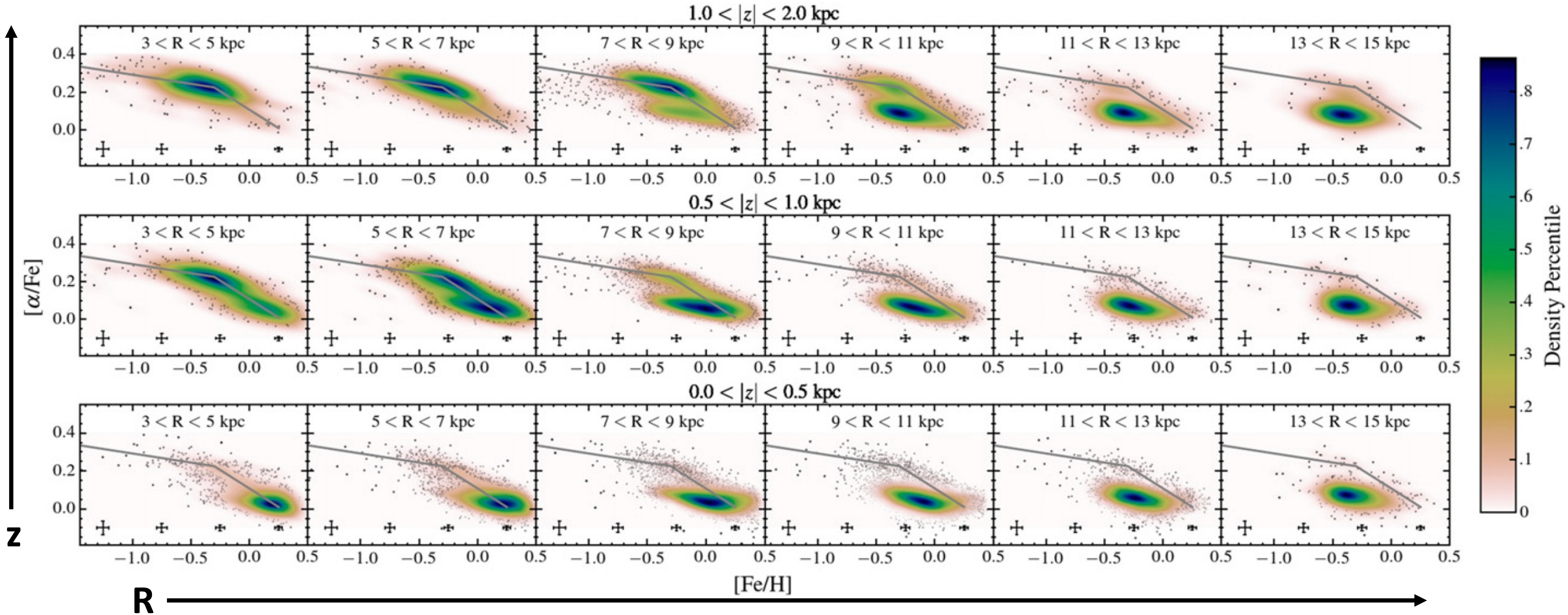
Metallicity structure of the thin and thick disk



At even higher distances from the plane, inner regions are almost all thick disk. Outer regions still look similar at all heights; high Z stars in the outer disk are not thick disk stars, they are probably just scattered thin disk stars.

Metallicity structure of the thin and thick disk

Hayden+15



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Milky Way Disk: Inferences on Formation and Evolution

Thin disk

- Formed through continuous, on-going star formation: Mix of stellar ages, smooth metallicity distribution, solar [α/Fe] ratios

- Hints of "inside-out" formation: metallicity gradient (maybe also the age-metallicity relationship?) shows inner regions more chemically evolved, maybe formed a bit faster than outskirts

- Dynamically calm process (low velocity dispersion)

Thick disk

- Formed earlier (lower metallicity) and faster (higher [α/Fe] ratios) than the thin disk.

- More centrally concentrated process (shorter radial scale length)

- More "dynamically active" process (higher velocity dispersion)

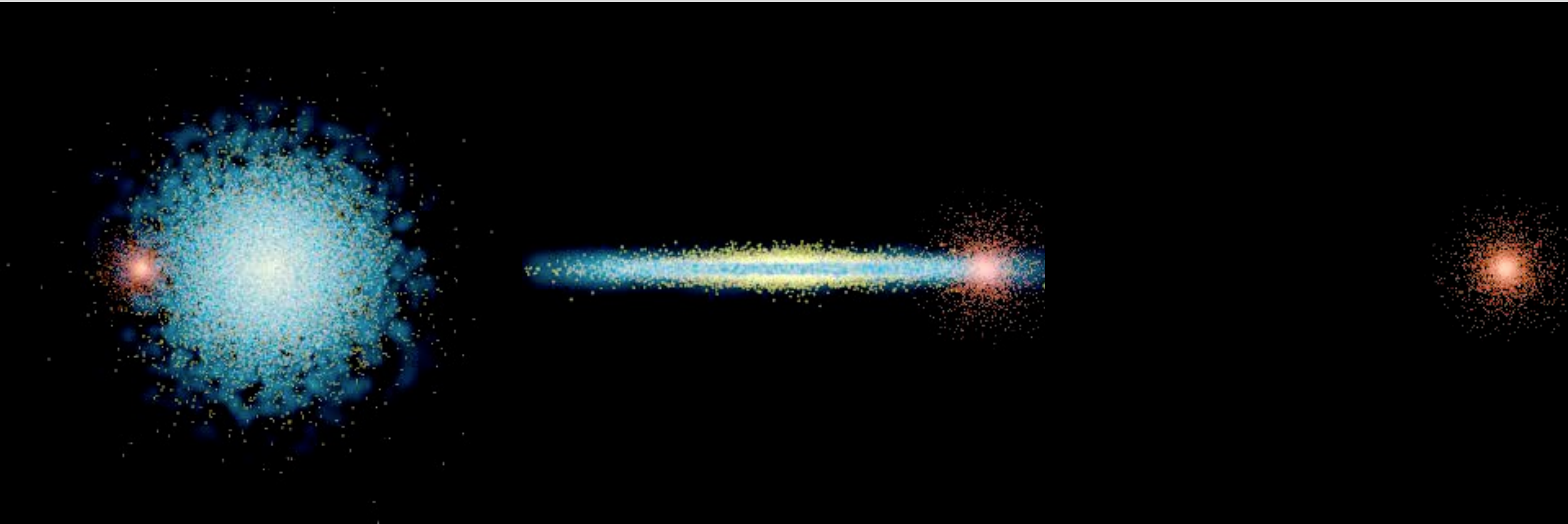
Thick Disk Formation Scenarios I : Early Satellite Accretion

***Astronomy lingo**: in terms of dynamics, "cold" means ordered motion with low velocity dispersion, while "hot" means disordered motion with high velocity dispersion. Disks are "cold", bulges and ellipticals are "hot".*

Early in the Milky Way's history, a LMC-ish satellite fell in and heated (scattered) existing disk stars. ⇒ thick disk

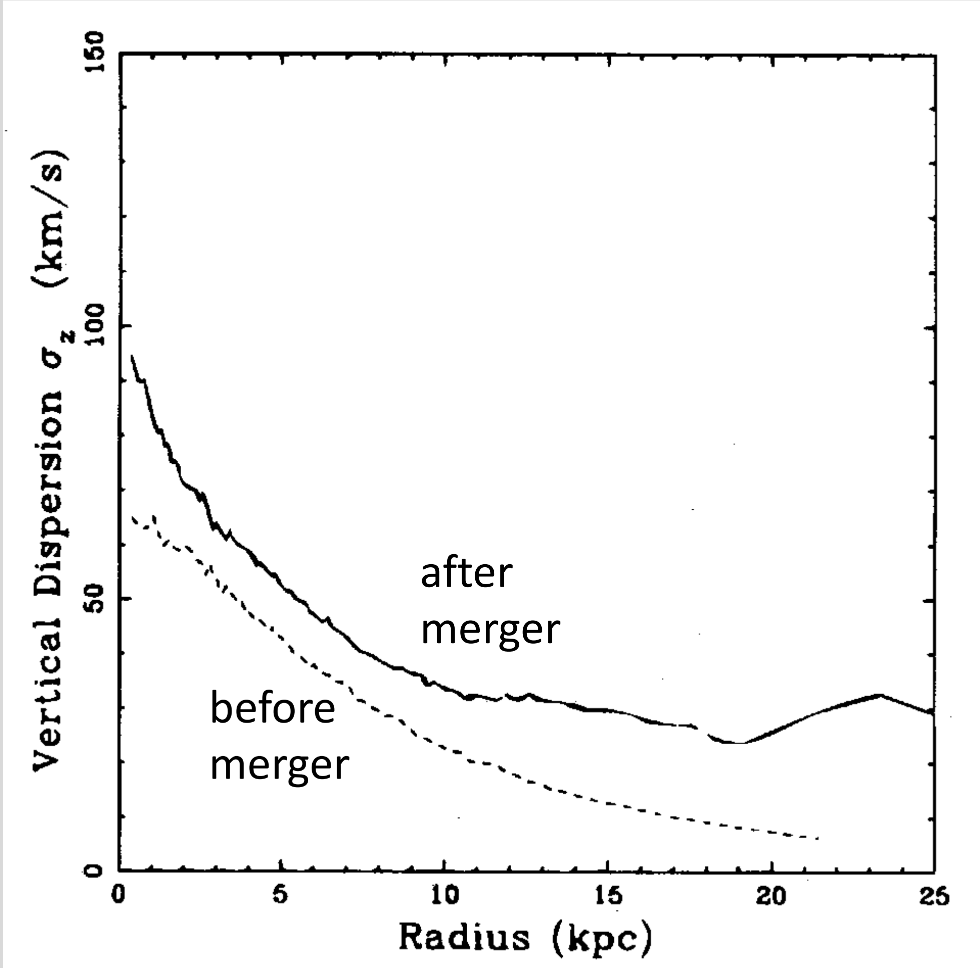
Afterwards, the gas re-settles into the disk and continues forming stars. ⇒ thin disk

Mihos & Hernquist 1995



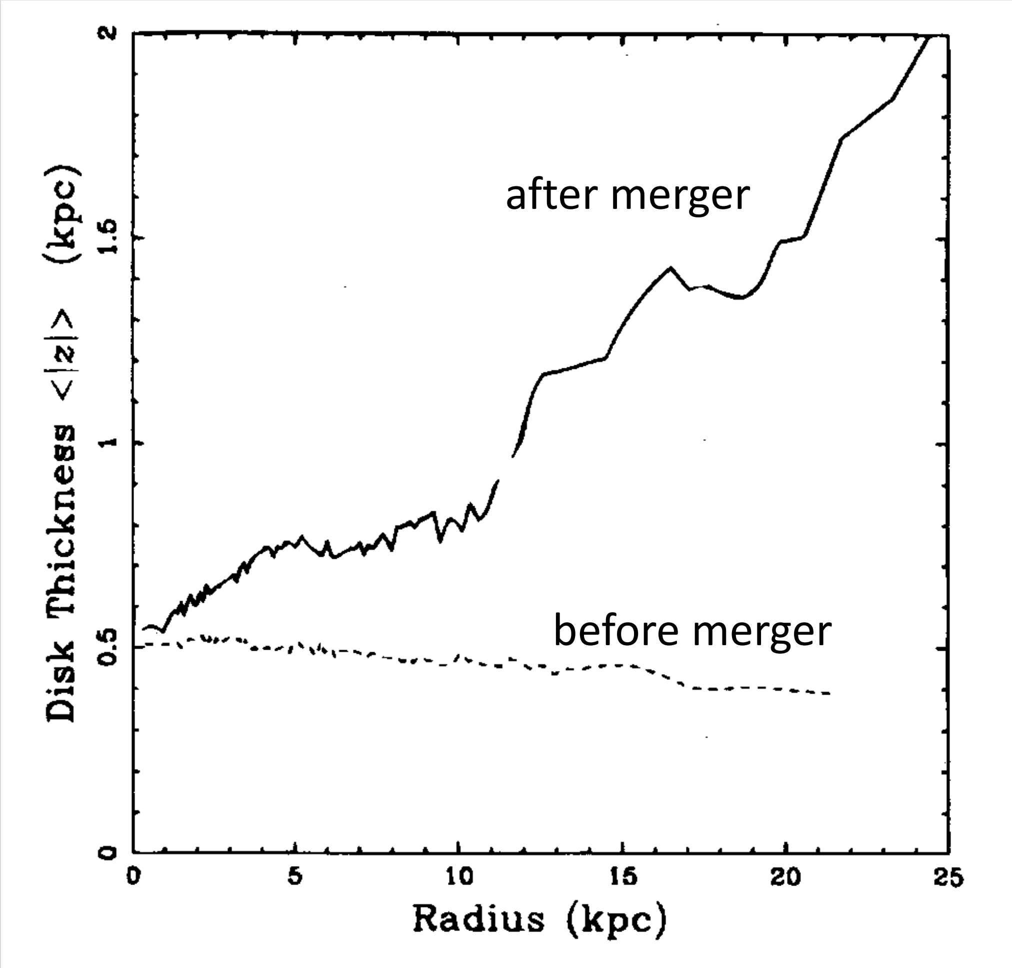
Thick Disk Formation Scenarios I : Early Satellite Accretion

As the satellite falls in, it stirs up the orbits of stars and increases their velocity dispersion (random motion).



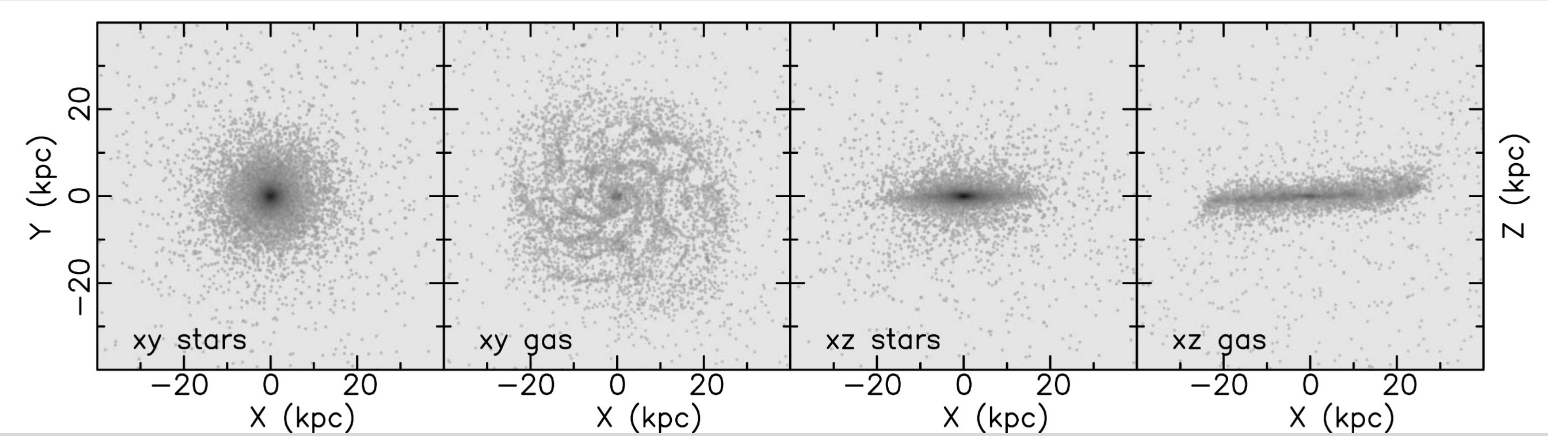
Walker+ 96

This "disk heating" puffs up the existing disk and makes it thicker.

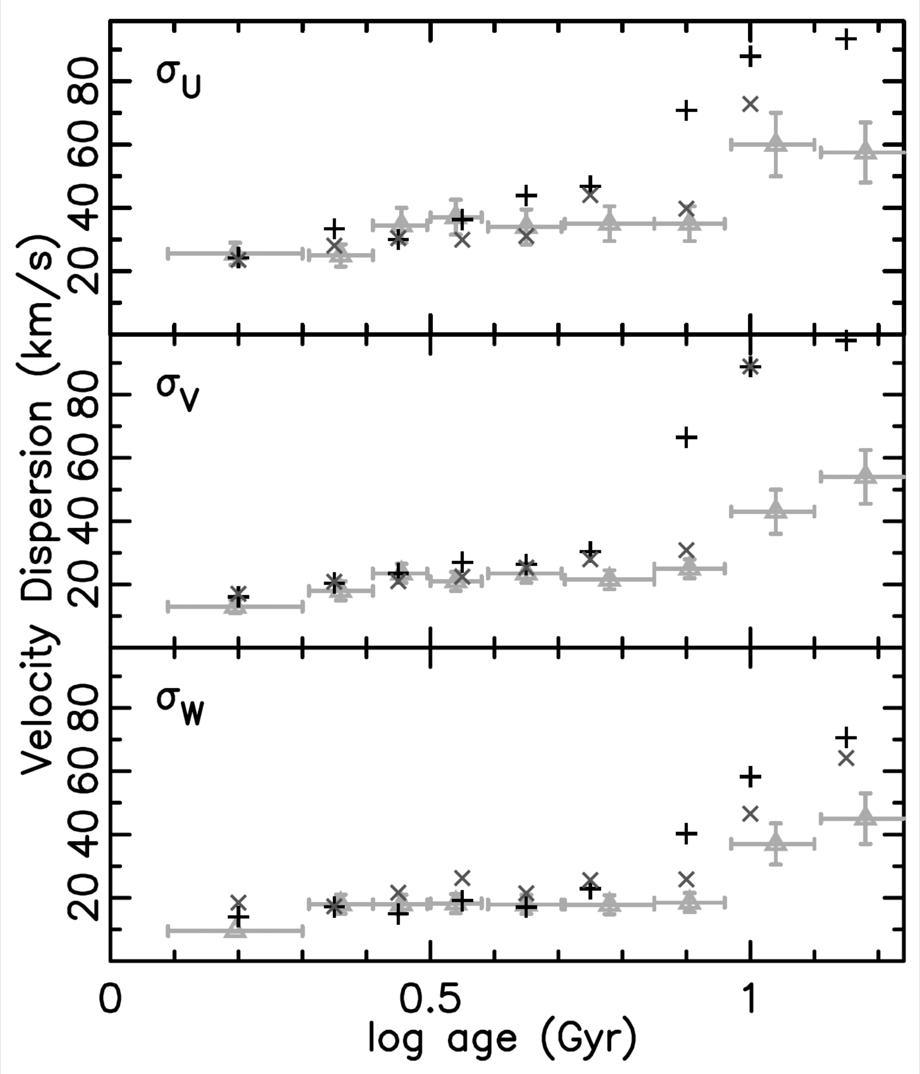


Thick Disk Formation Scenarios II : Turbulent Disk Formation

Simulated galaxy disk **at current time**… (Brook+ 04)



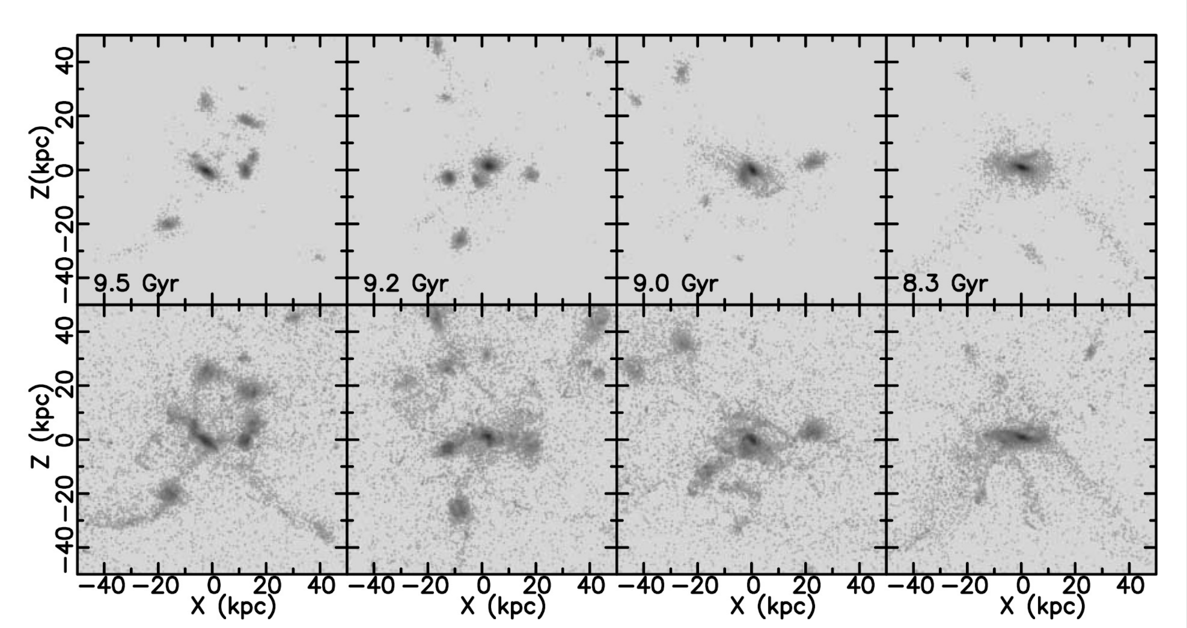
… has a disk that shows a velocity dispersion that increases with stellar age…



Simulations: +, ×

Observations: ▲

…because **back when the disk formed** it was very clumpy and turbulent



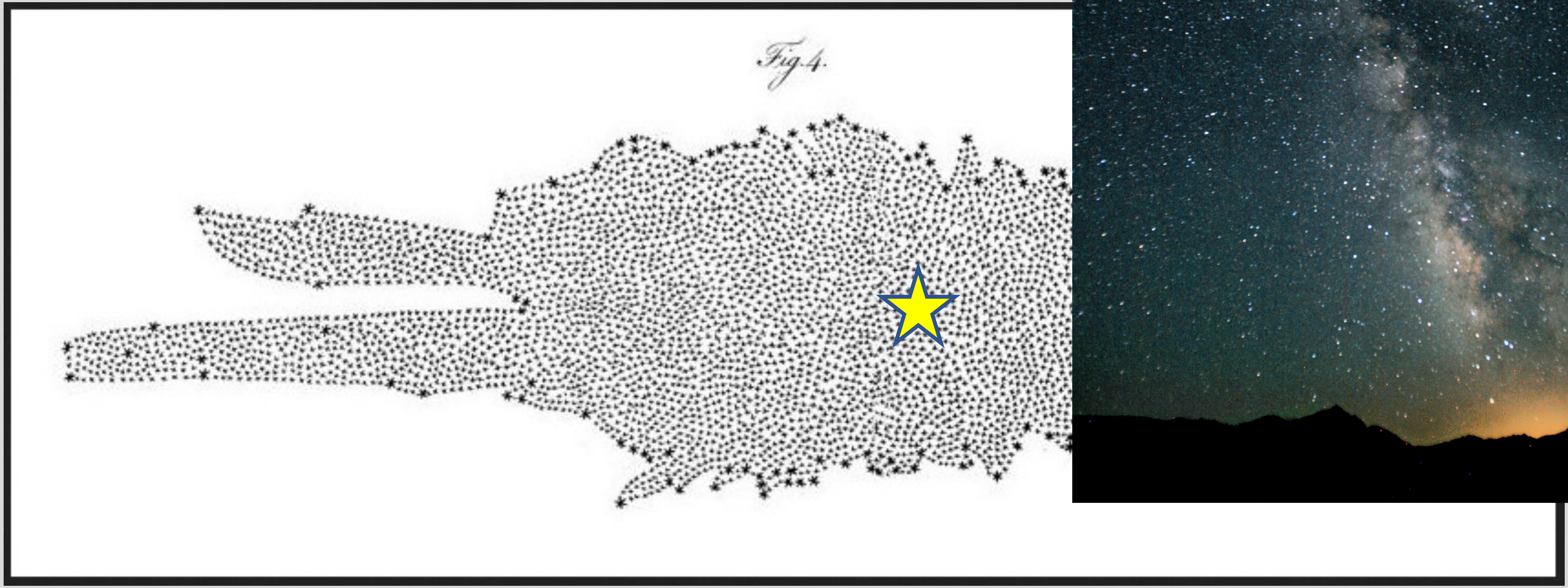
Gas

Stars

The Distance to the Galactic Center

1785: William and Caroline Herschel map the Milky Way using star counts and find the Sun near the center of the Galaxy.

Oops. In hindsight what went wrong?

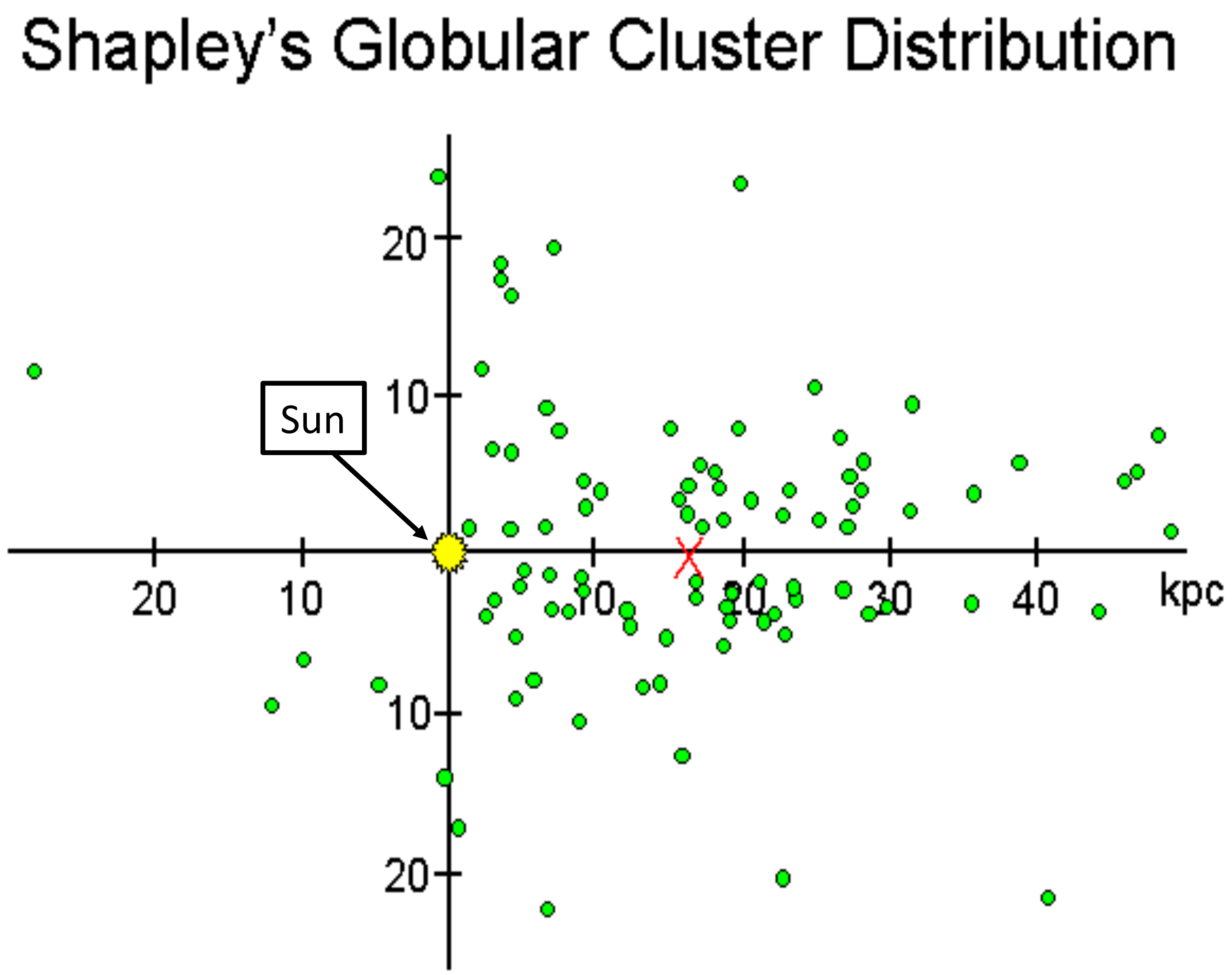


The Distance to the Galactic Center

1920: Curtis Shapley uses spatial distribution of globular clusters, finds that they are centered on a different. spot in the Milky Way.

Correctly reasons that globulars were centered on the location of the Galaxy's center, but incorrectly placed it 18 kpc away.

Why did he get it wrong?

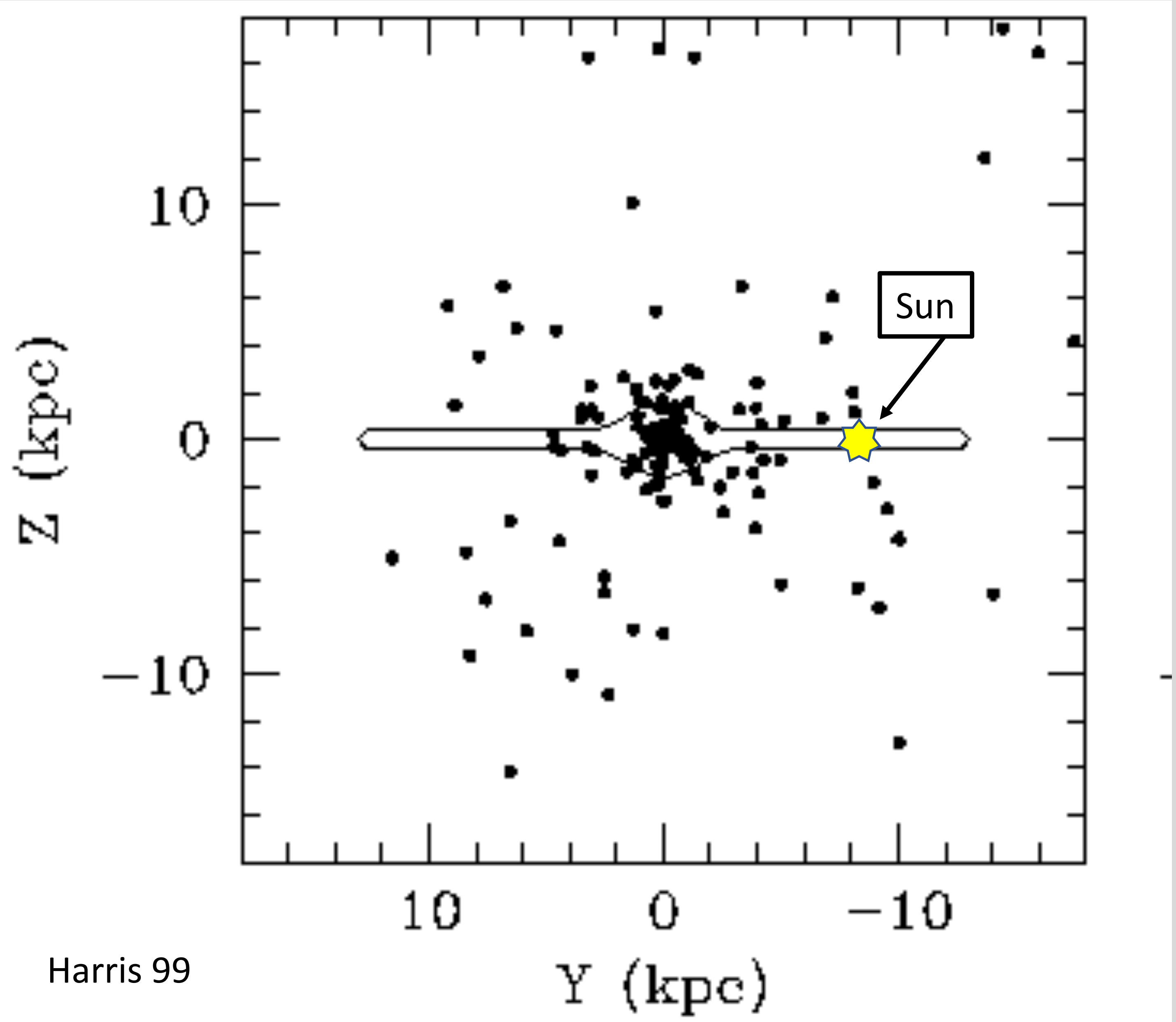


courtesy Rick Pogge, OSU

The Distance to the Galactic Center

Modern view of globular cluster distances and other tracers gives $R_\odot \approx 8 - 8.5$ kpc.

Shapley over-estimated the distance to the globulars because he didn't account for dust. Dust makes the clusters look dimmer, so Shapley thought they were further away.



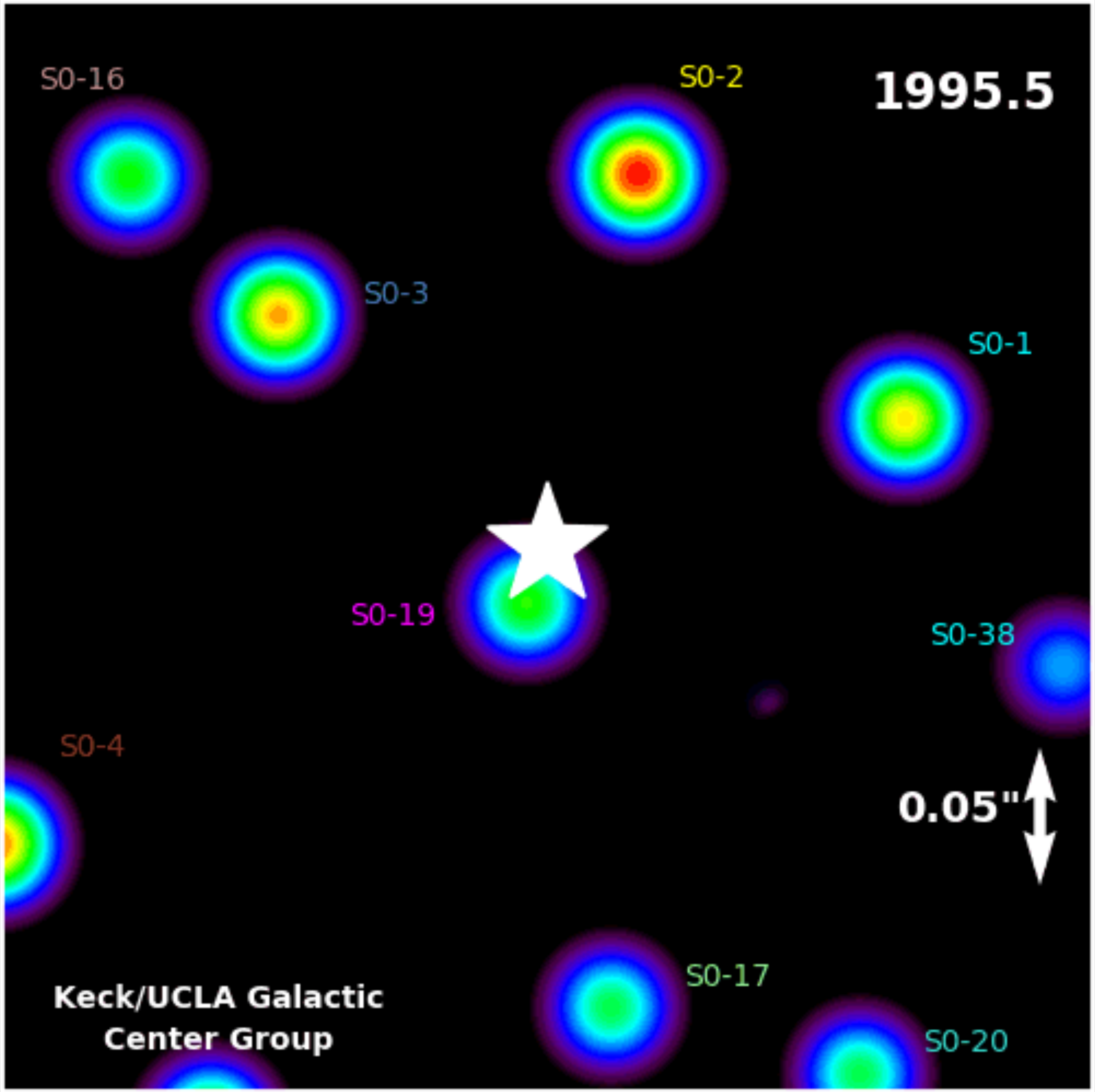
The Distance to the Galactic Center

Geometric distance:

Infrared interferometry follows the proper motion of stars and gas clouds orbiting the black hole at the Galactic center.

Orbits are Keplerian (BH is a point mass).

We can measure the stars orbital proper motion.



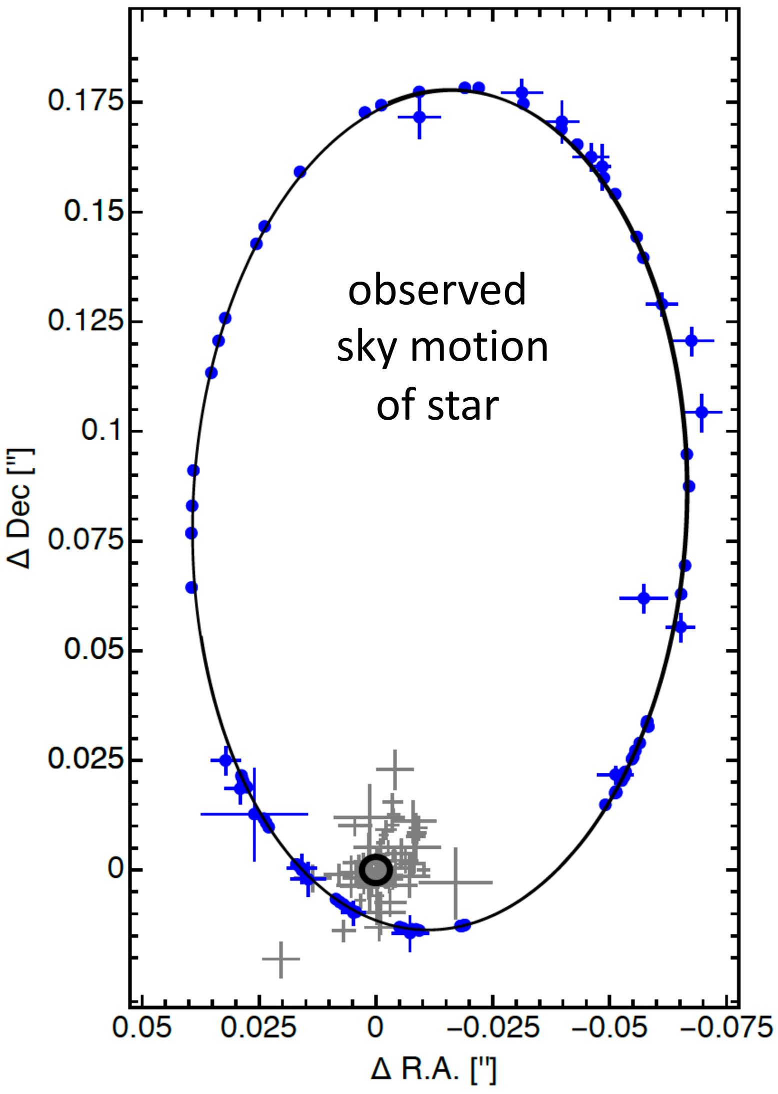
The Distance to the Galactic Center

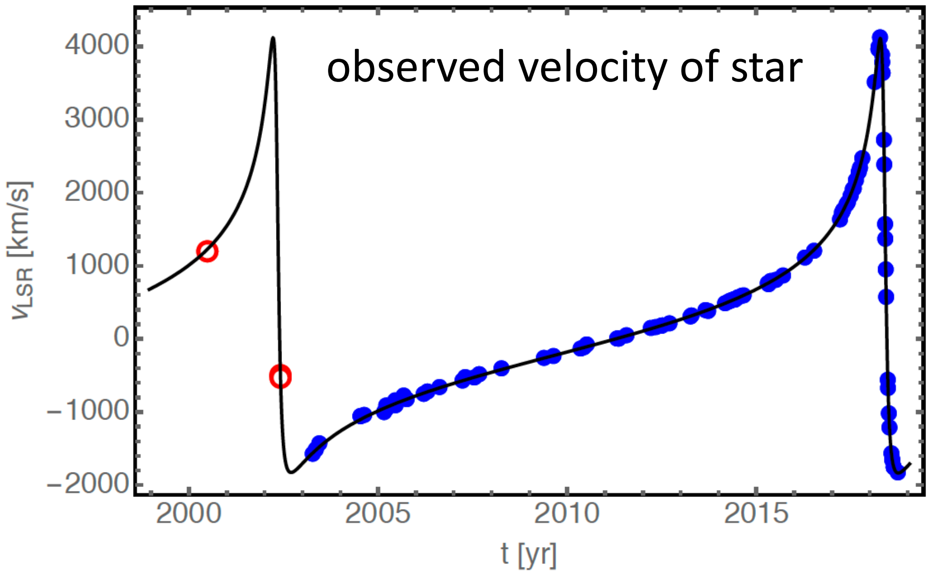
GRAVITY collaboration (Abuter+ 2019)

Geometric distance:

Infrared spectroscopy gives velocity of the objects as well.

Velocity and proper motion connected by distance.





d = 8178 pc ± 13$_{stat}$ ± 22$_{sys}$.

(that's a 0.3% uncertainty!!!)

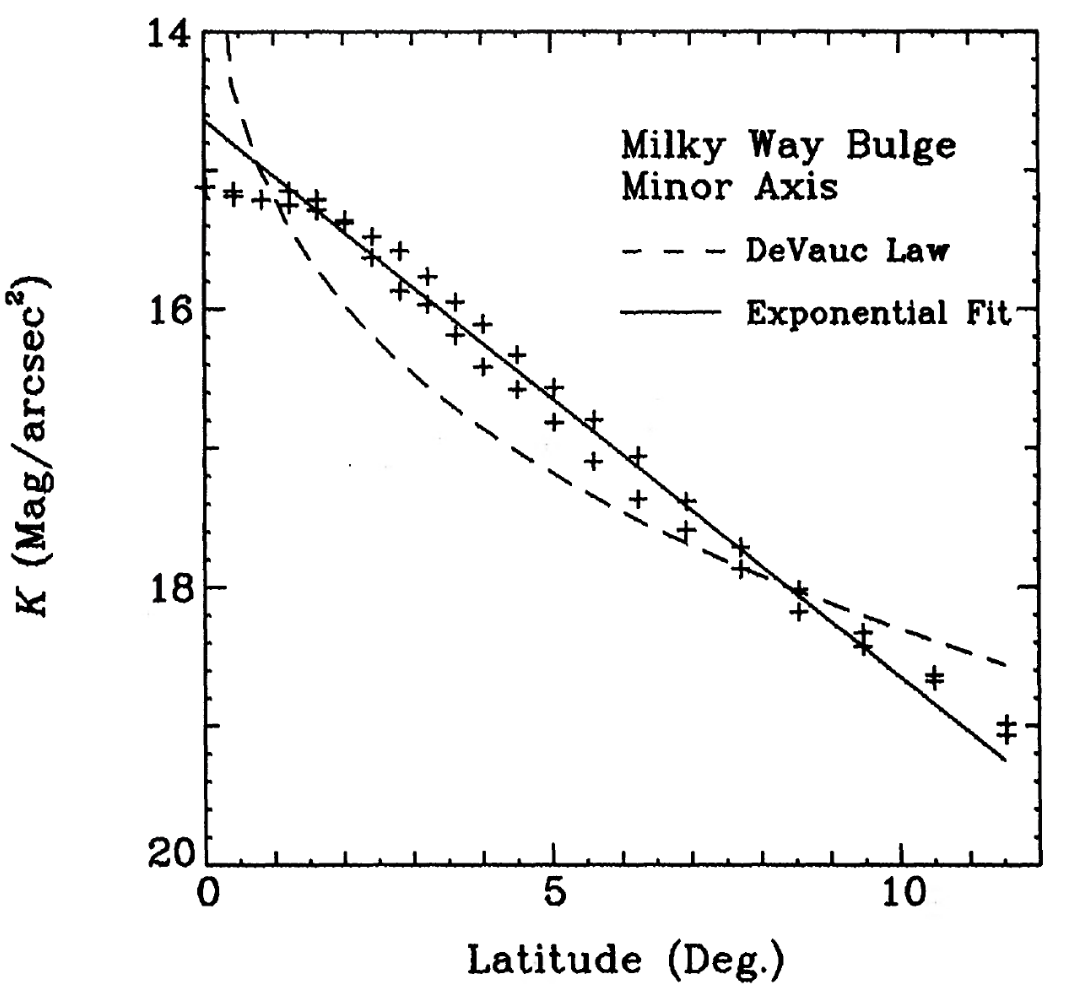
The Milky Way's Bulge

Classically viewed as an $R^{1/4}$ spheroid with $r_e \approx$ 2.7 kpc (optical star counts; de Vaucouleurs & Pence 78). But even de Vaucouleurs classified the Milky Way as a barred spiral!

FIG. 6. An impression of the morphology implied by the SAB(rs)bc II classification and consistent with the spiral pattern derived by Y. M. and Y. P. Georgelin from the distribution of HII regions.

Kent+ 91 points out that its surface brightness profile is better fit by an exponential than a de Vaucouleur $R^{1/4}$ law.

More like a disk?



The Milky Way's Bar

Other hints from gas kinematics and photometry that the Milky Way might have a bar. Best evidence came from near IR imaging by the COBE satellite.

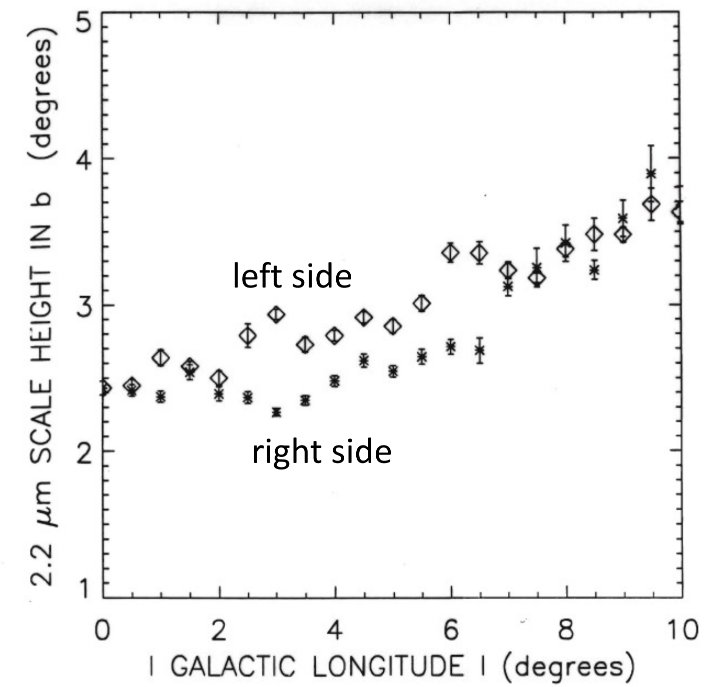
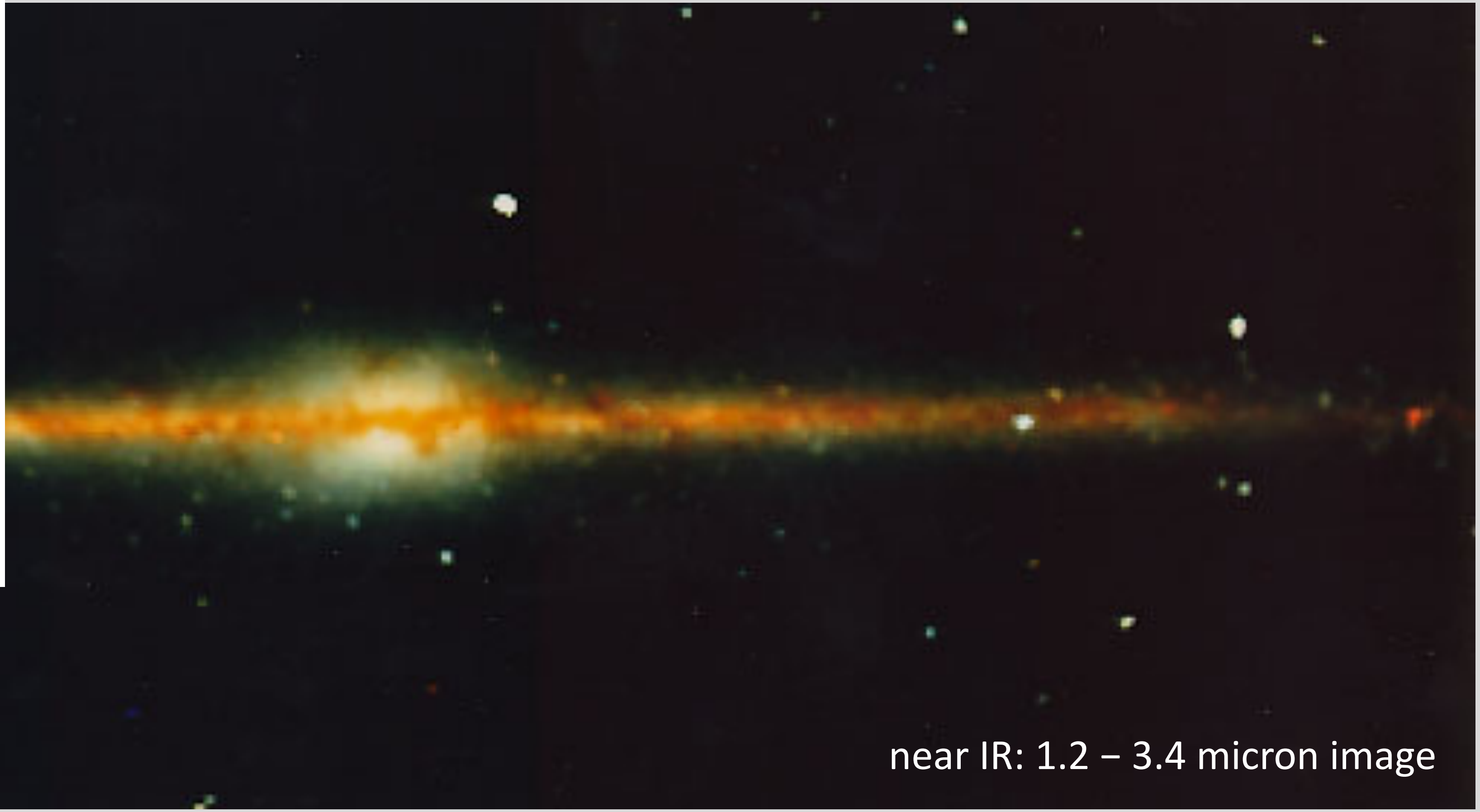


FIG. 2.—2.2 μm angular scale heights at fixed longitude. Scale heights for $l < 0°$ are represented by asterisks, whereas diamonds are for scale heights at positive Galactic longitudes. The error bars represent 1 σ errors on the computed scale height.

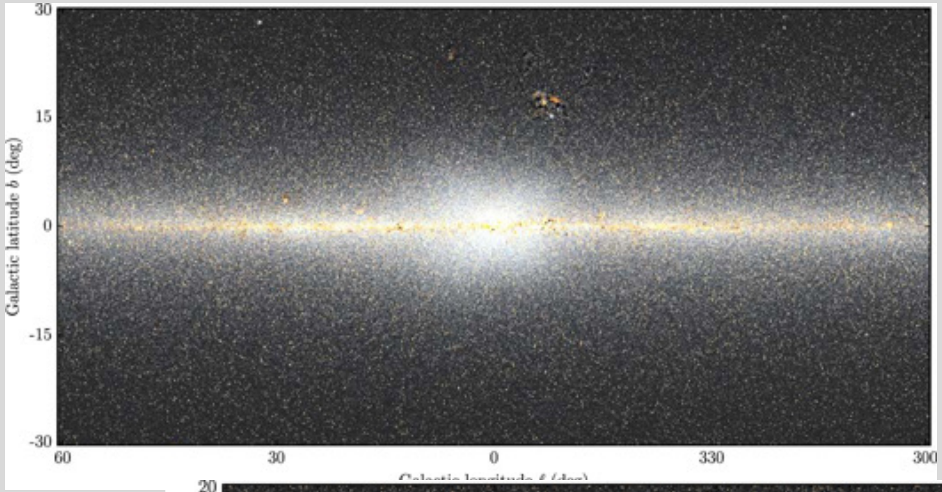
⇐Apparent vertical thickness of the bulge on either side of the Galactic center. One side appears thicker because it is closer: a bar, not a round bulge.

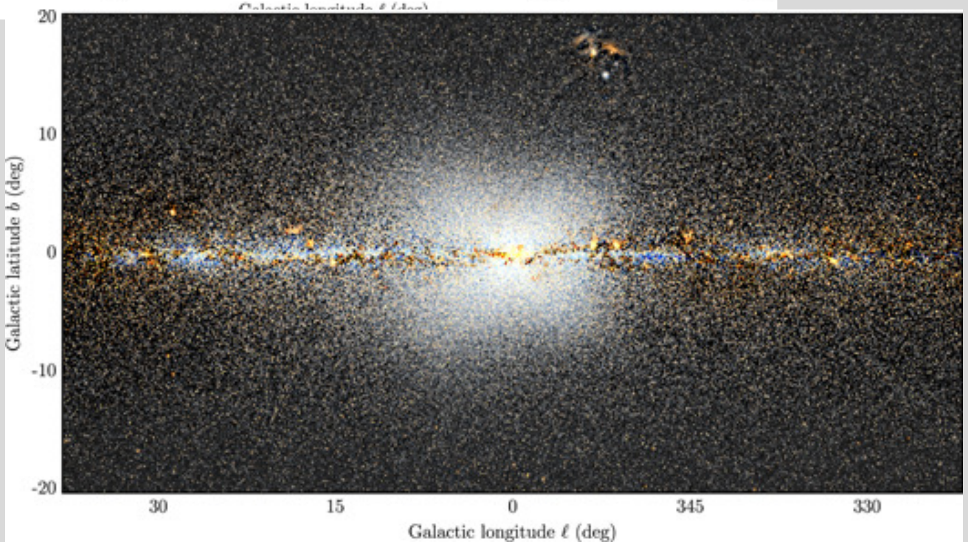


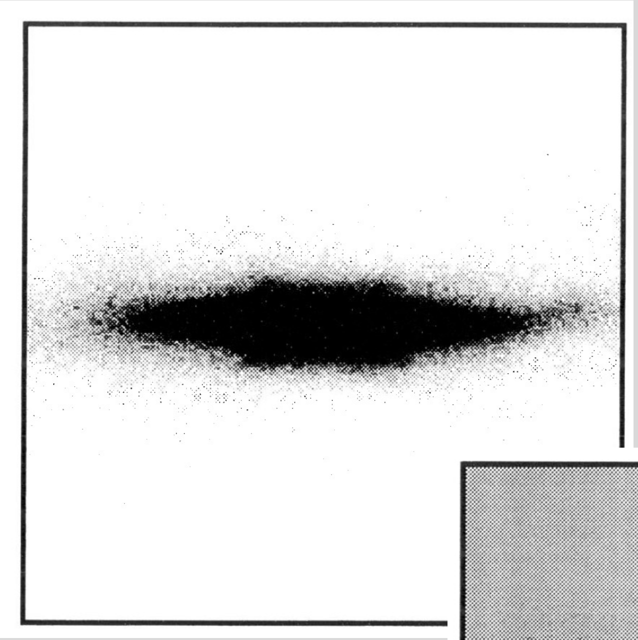
The Milky Way’s Bar

Bars are a natural dynamical instability in rotating disks. They buckle vertically, giving the impression of a peanut-shaped or X-shaped bulge.

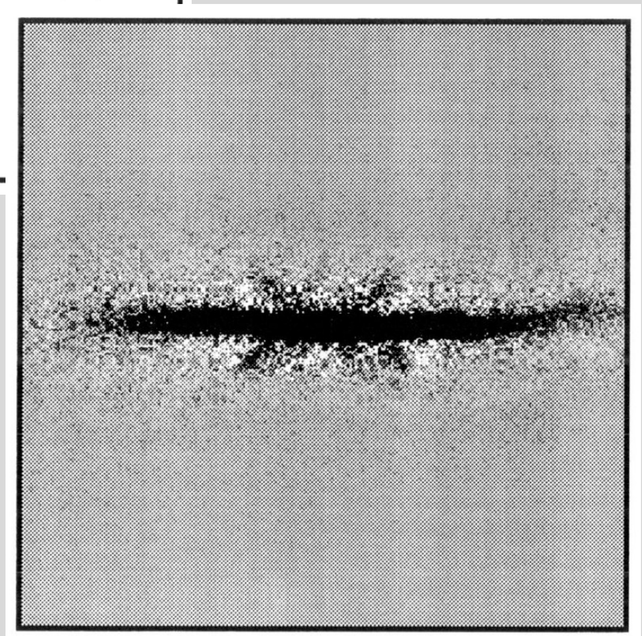
WISE near-IR imaging (Ness & Lang 16)







Barred galaxy simulation (Mihos+ 95)



YouTube animations of bar instabilities:

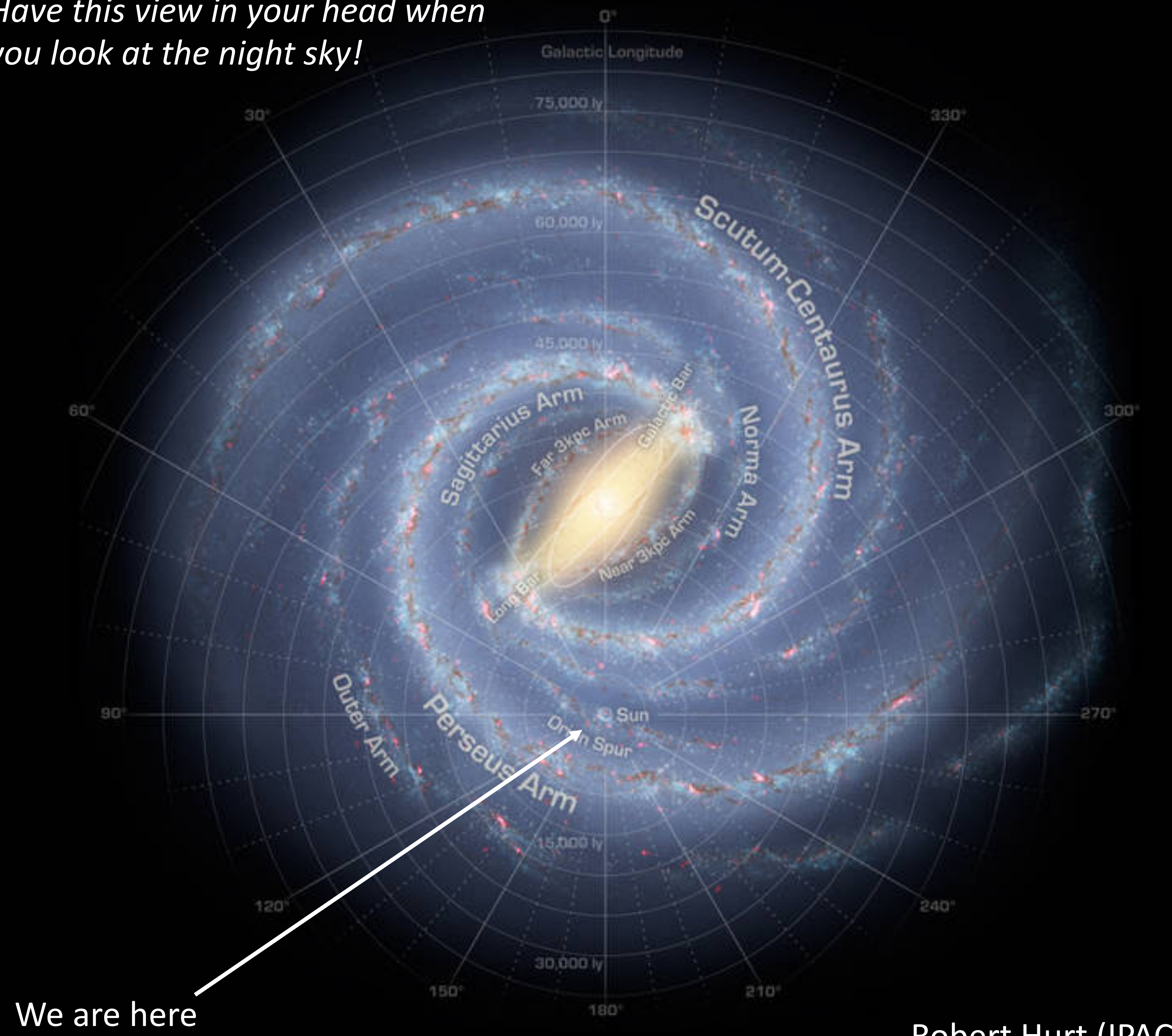
- Face on view
- Edge on view

The Milky Way's Bar

The structure and kinematics of the inner galaxy are well-explained by a barred inner disk – no need to invoke a separate "bulge" component.

But it often still gets called a bulge….

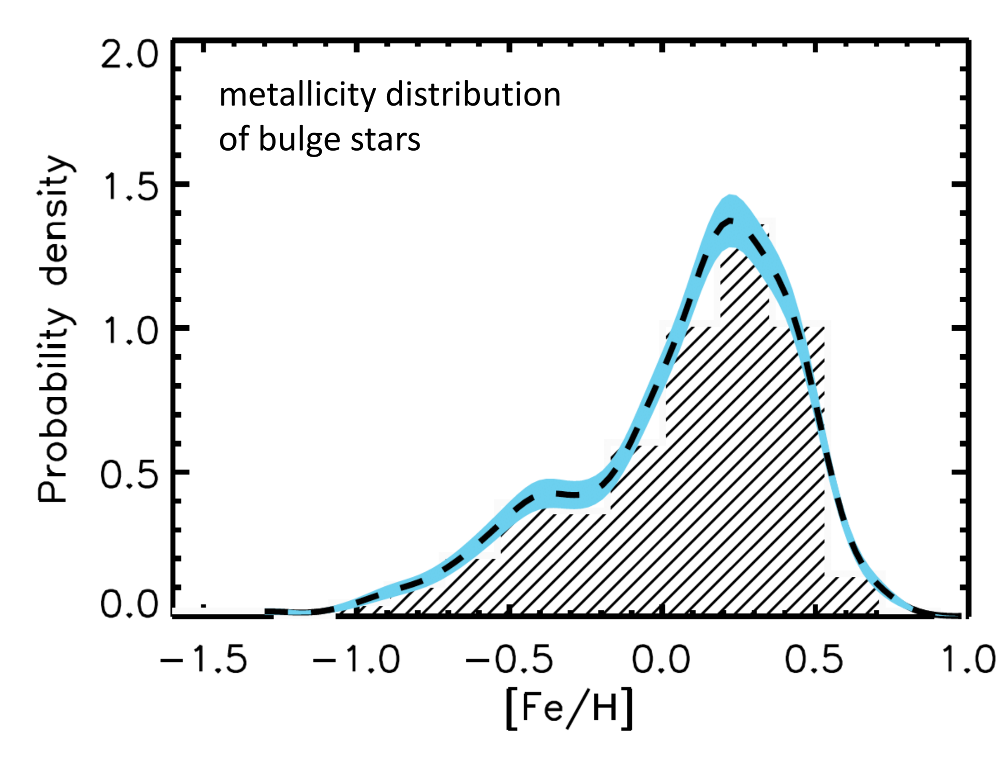
Have this view in your head when you look at the night sky!



Robert Hurt (IPAC)

Metallicity in Bulge/Bar/InnerDisk

Gonzalez+ 15



Bulge stars show a wide range of metallicity, ranging to metal-poor to super-solar values.

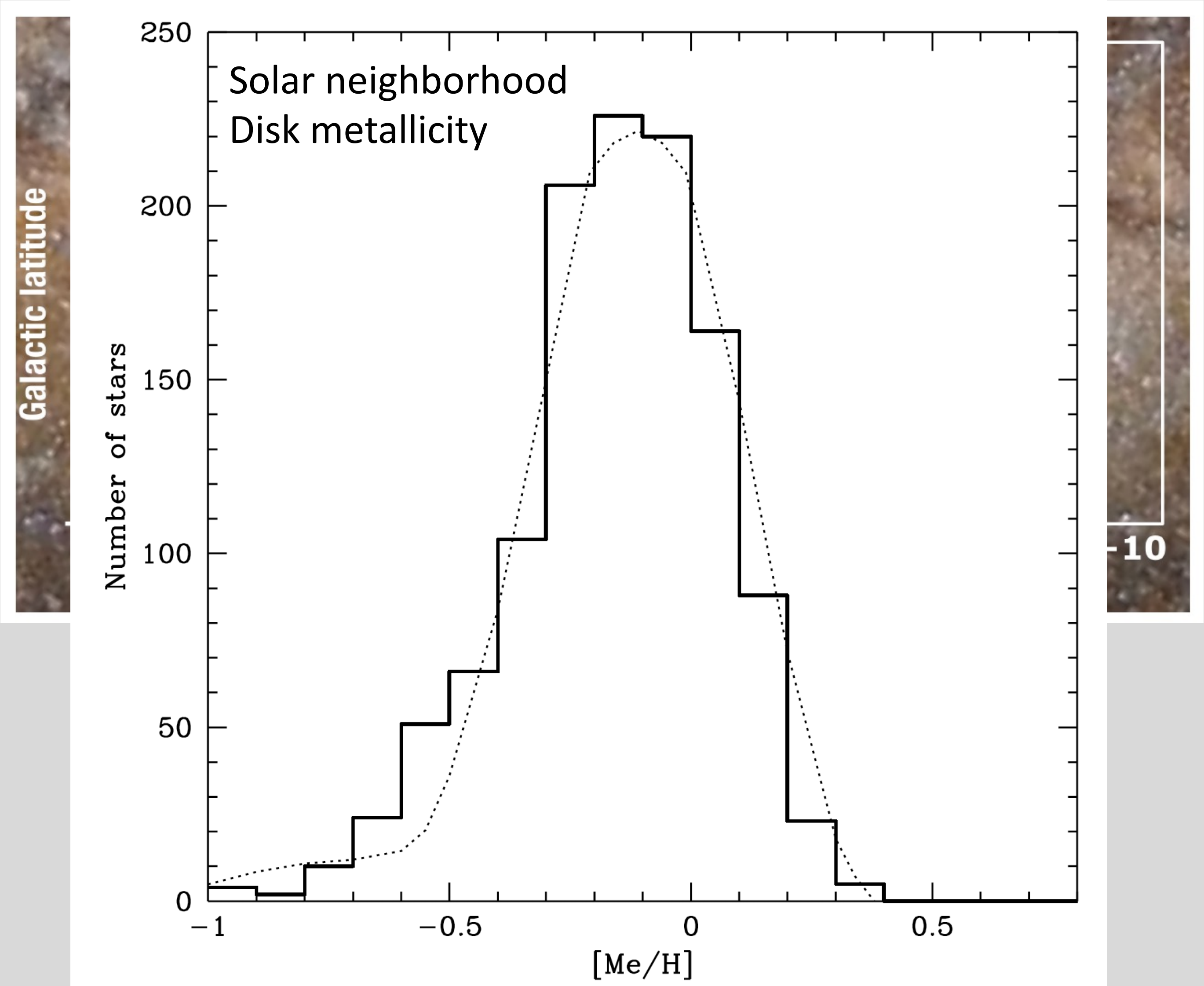
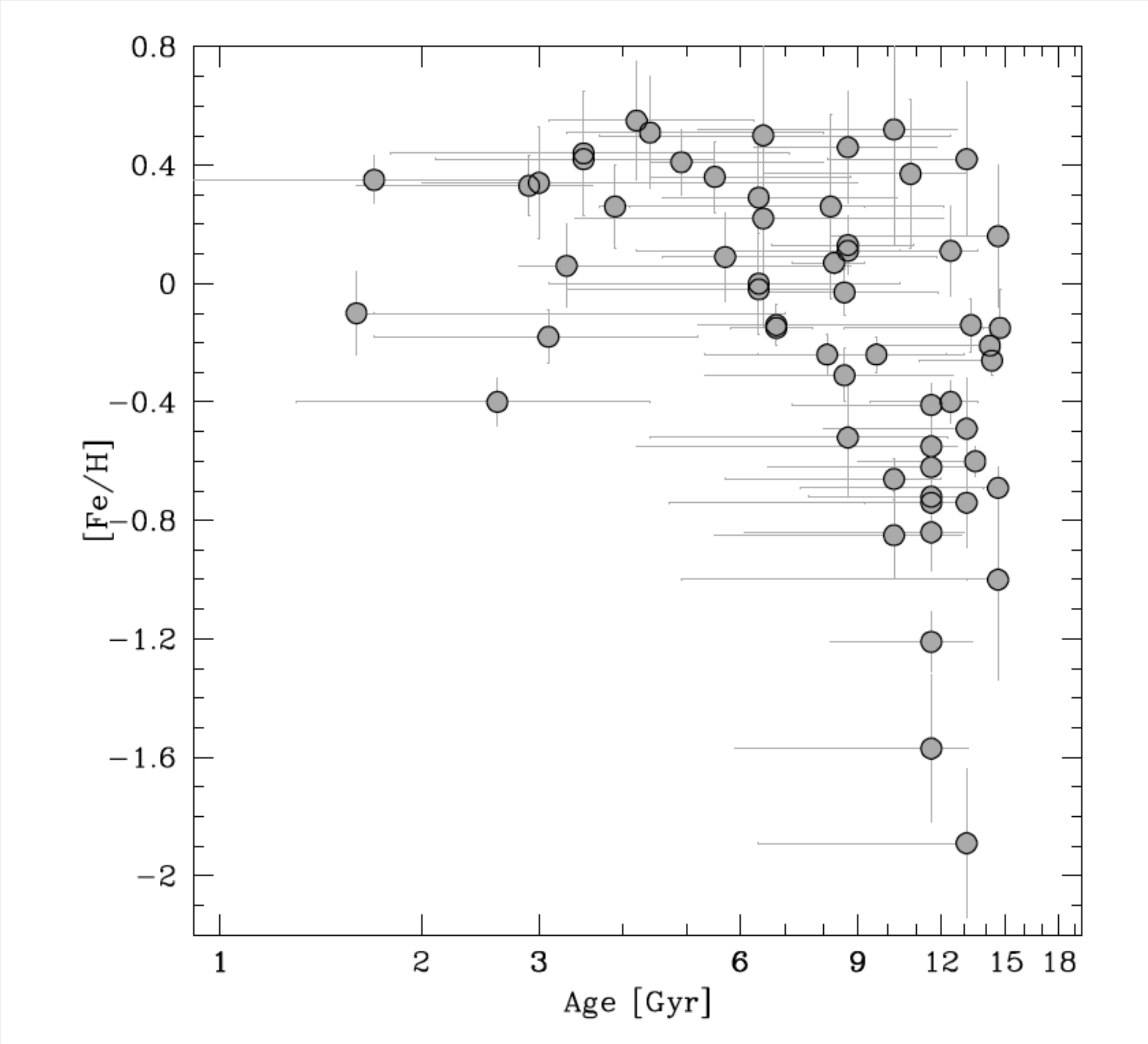


Fig. 26. Distribution of metallicities for the volume complete sample of single stars (full histogram). For comparison the dotted curve shows the reconstructed distribution for G dwarfs from Jørgensen (2000), which is corrected for scale height effects and measurement errors.

Age Distribution in Bulge/Bar/InnerDisk

Bulge stars show a range of ages, but are predominantly old (>8 Gyr).

Many of the oldest stars have high metallicity: *Metallicity enrichment can happen fast.*



Bensby+13

Metallicity in Bulge/Bar/InnerDisk

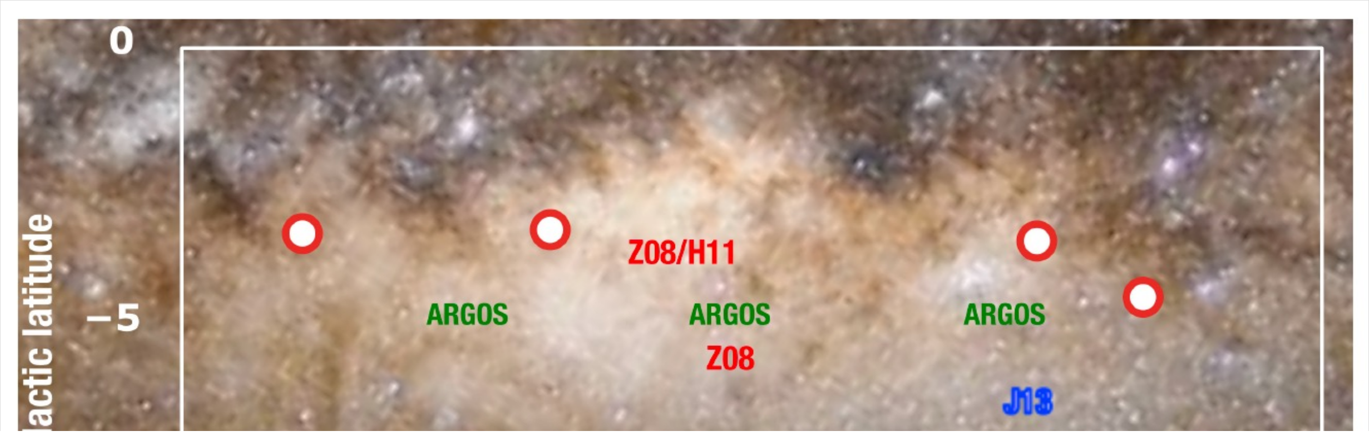
Gonzalez+ 15

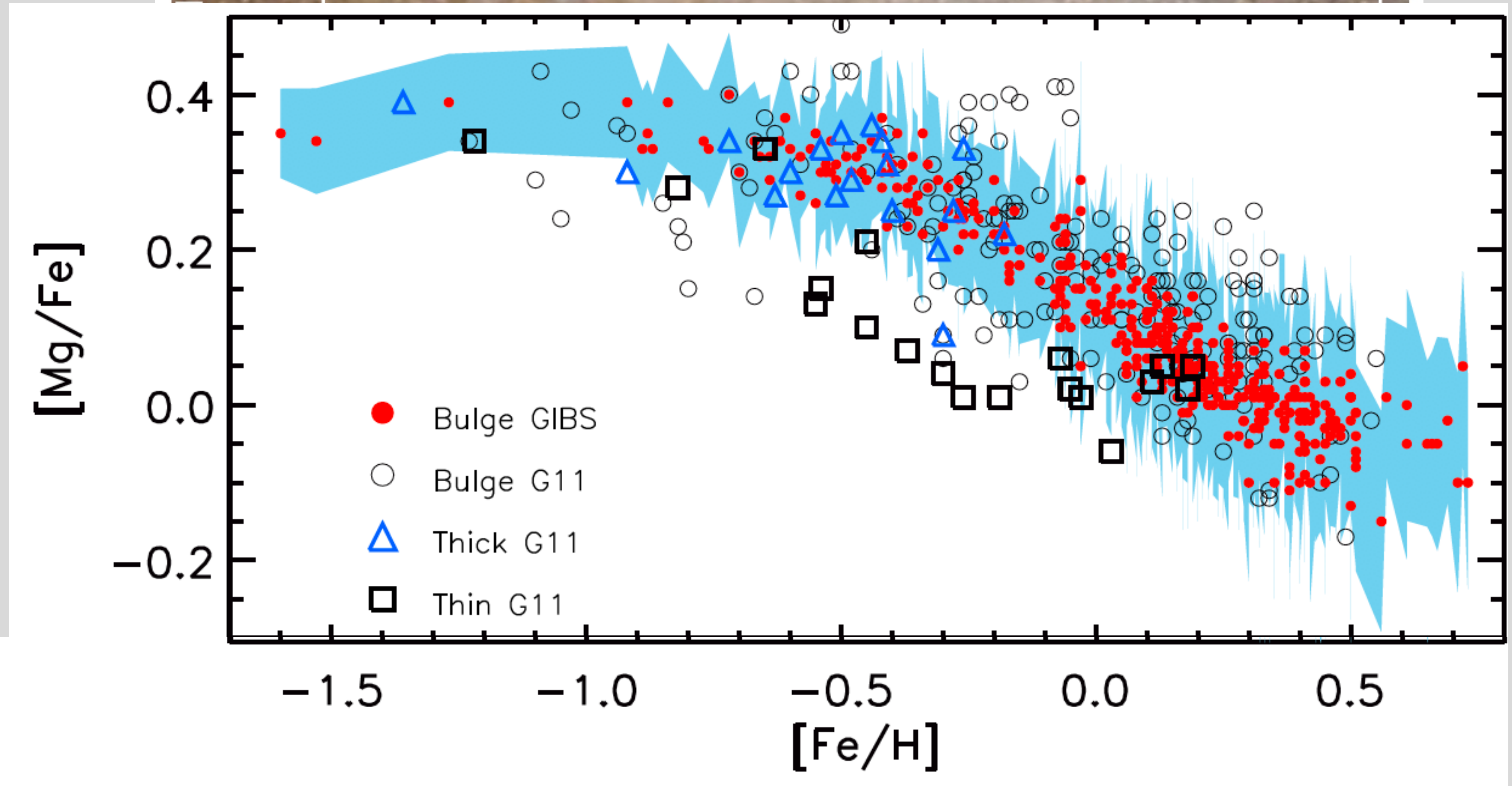
Bulge stars show enhanced α-elements relative to disk stars.

Indicative of an early period of rapid star formation, leading to a population of stars which is now old, α-enhanced, and with a wide range of metallicity.

“Inside-out galaxy formation” : inner regions form first and rapidly, outer regions (thin disk) form more gradually over time.

Thick disk is somewhat “in between”





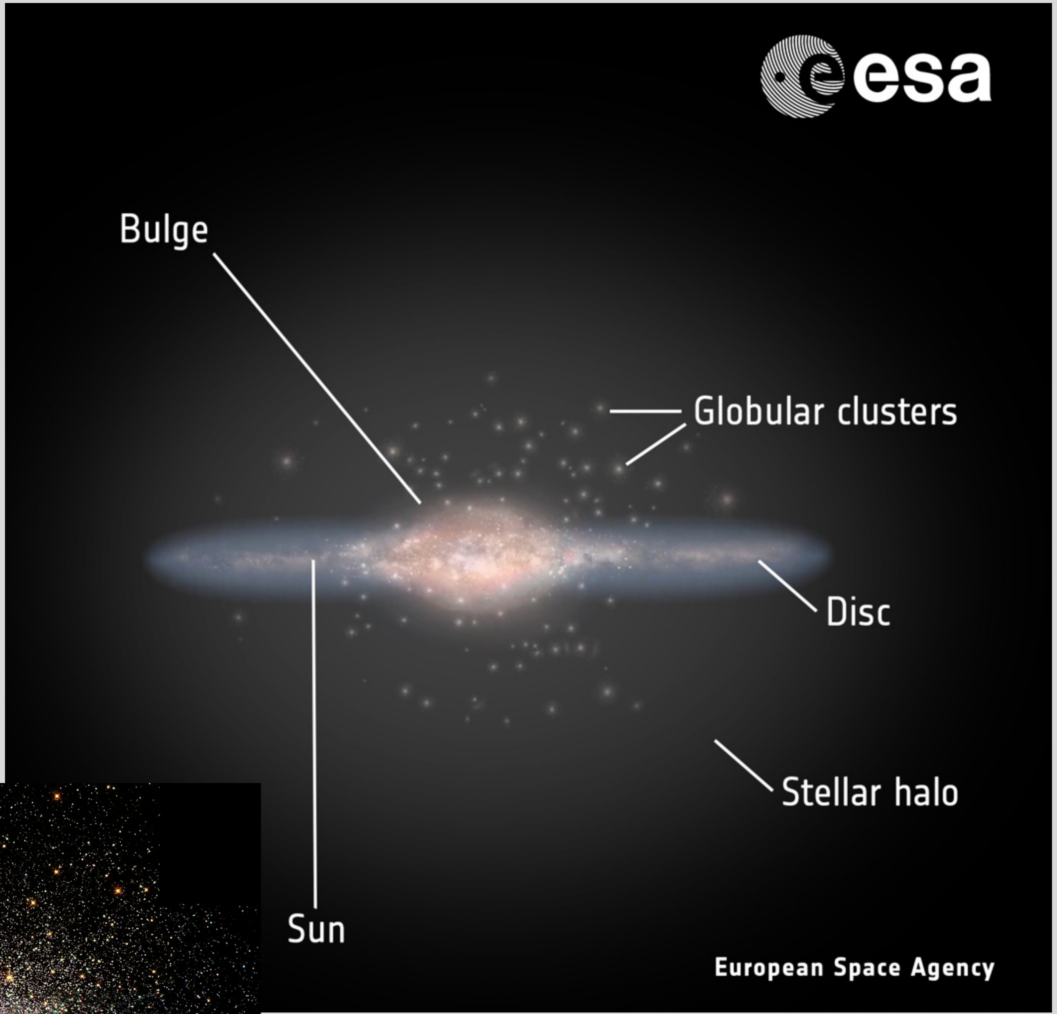
The Milky Way's Stellar Halo

The Milky Way is surrounded by an extended, spheroidal, and sparse population of old stars: the stellar halo.

The projected surface brightness is extremely low: μ_V fainter than 30 mag/arcsec^2. Cannot detect diffuse light this faint in other galaxies, unless they are close enough (dist < few Mpc) to resolve their individual stars.

Embedded within the stellar halo is the Milky Way's globular cluster system.

Together, halo stars and globular clusters provide important clues to the Galaxy's evolutionary history.



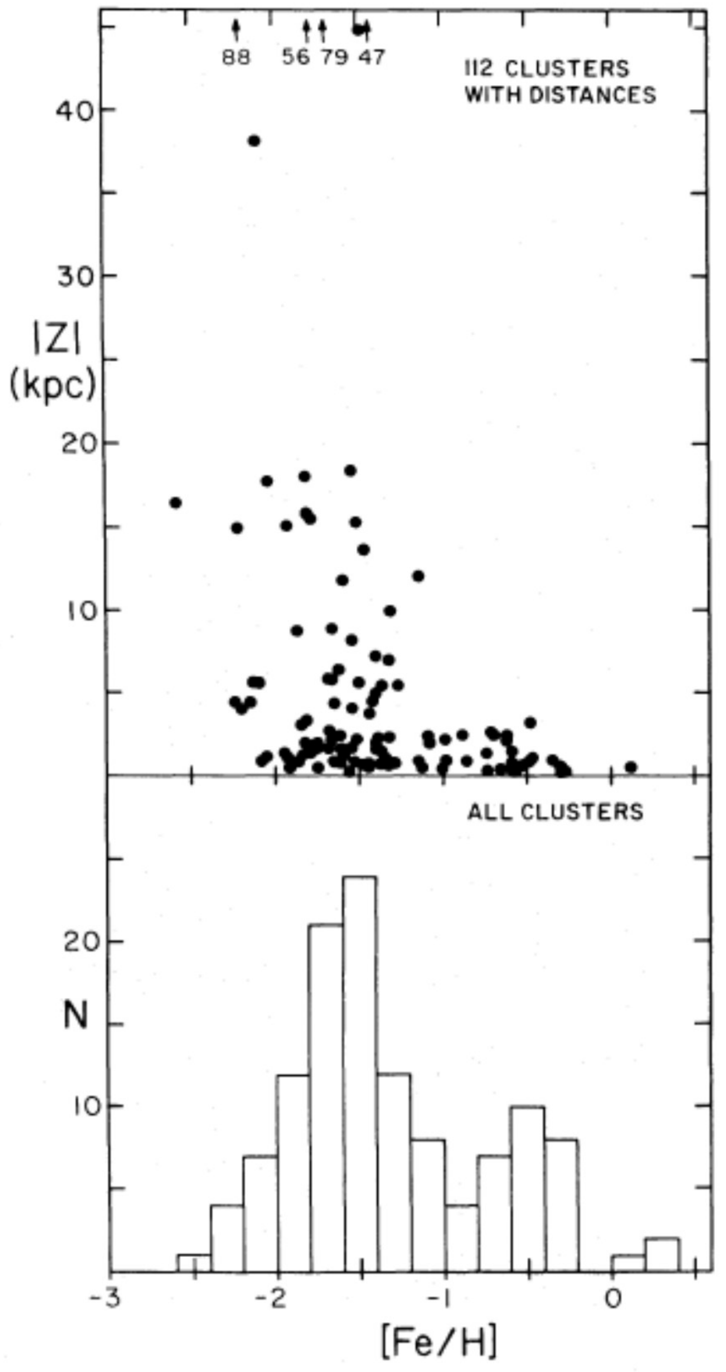
Studying the Stellar Halo: Globular Clusters

Advantage: Easy to see at large distances, can get good ages and metallicities.
Disadvantage: Biased tracer, only about 1% of the mass of the stellar halo.

Multiple component population:

- Outer halo, roughly spheroidal, random motions, [Fe/H] < −0.8
- Inner halo clusters, flattened component, rotating with disk, [Fe/H] > −0.8

Zinn 85



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Number density of globular clusters falls off with radius roughly as $\rho \sim r^{-3.5}$

Zinn 85

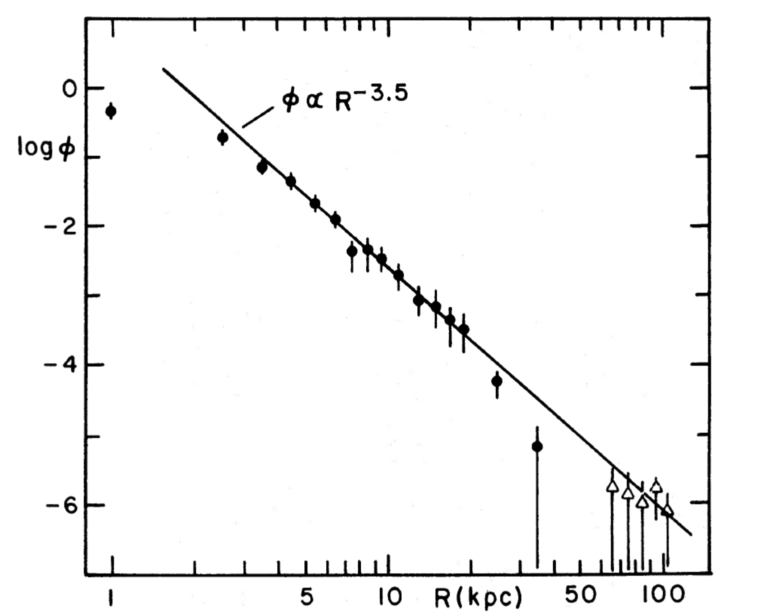
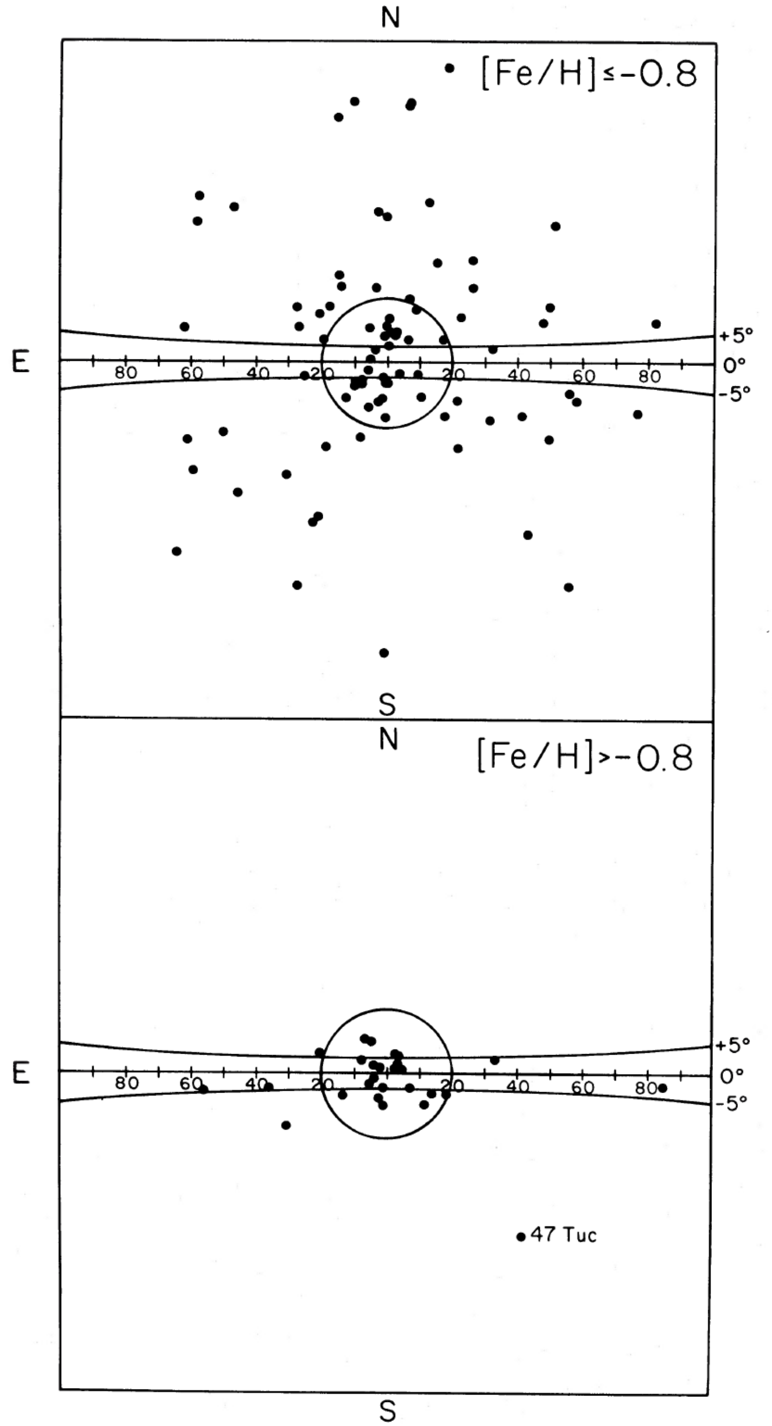


FIG. 2.—The number of clusters per cubic kiloparsec (ϕ) is plotted against galactocentric distance (R). The solid circles represent the clusters with $|Z| < 20$ kpc; the open triangles represent the clusters with $|Z| > 37$ kpc. There are no clusters in the zone $33 < R < 60$ kpc.

Number of clusters per cubic kpc, as a function of radius.



Studying the Stellar Halo: RR Lyrae Stars

Advantage: Relatively luminous, give good distances.
Disadvantage: A rare subset (specific evolutionary phase) of a sparse population.

[Layden (1995)](): Nearby (d<2.5 kpc) RR Lyraes

−2.0 < [Fe/H] < −1.5 (very metal poor): $\sigma_{los} \approx 120$ km/s, $v_{rot}/\sigma_{los} \approx 0$
−1.0 < [Fe/H] < 0.0 (moderately metal poor): $\sigma_{los} \approx 50$ km/s, $v_{rot}/\sigma_{los} \approx 4$

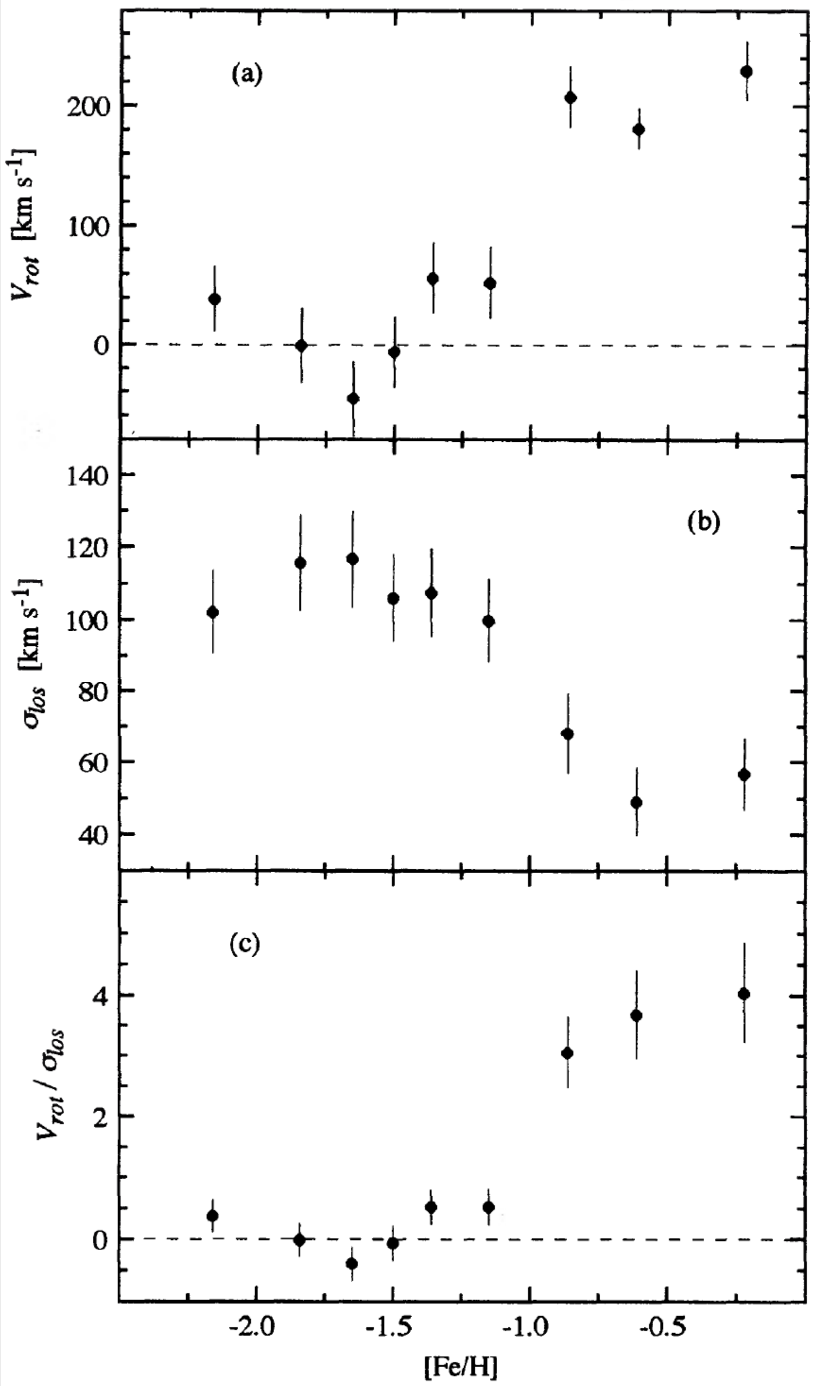
Average velocity relative to LSR:

<U> = -13 km/s
<W> = -5 km/s
<V> = 40 km/s [Fe/H] > −1.0 (moderately metal poor)
<V> = 200 km/s [Fe/H] < −1.0 (very metal poor)

Metal-poor RR Lyraes are likely a halo population with ages > 10 Gyr

⇒ halo is old, metal poor, and non-rotating

σ_{los} means observed radial velocity dispersion, along the line of sight.



Studying the Stellar Halo: Nearby Halo Stars

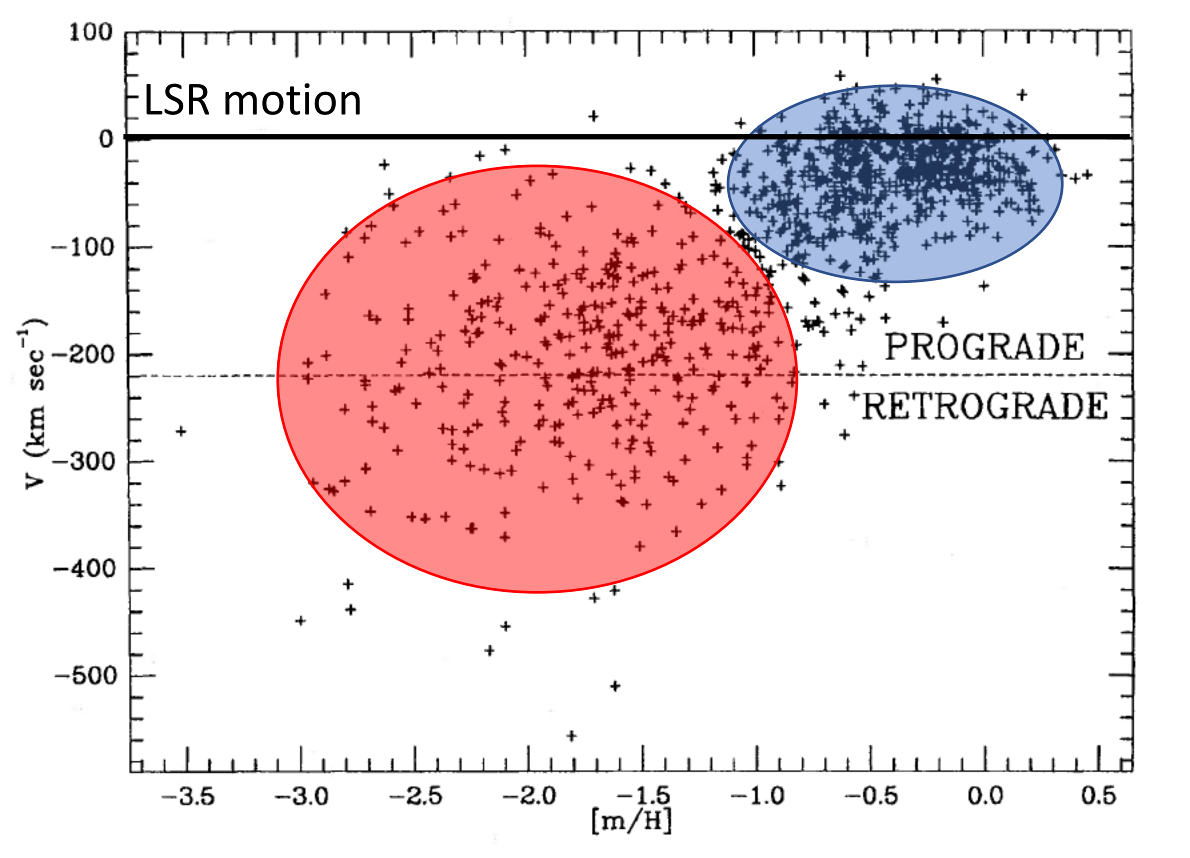
Advantage: Greater numbers (selecting all stars, not just a specific evolutionary type)
Disadvantage: Need to disentangle from disk population. halo:disk ratio is 1:1000. How?

If halo stars are not rotating along with the disk, they will be moving quickly relative to the Sun.
Look for stars with high proper motion!

High proper motion stars [(Carney+ 96)]()

Disk stars (high proper motion due to close distance)
Halo stars (high proper motion due to high velocity)

Halo stars show low metallicity, little net rotation.



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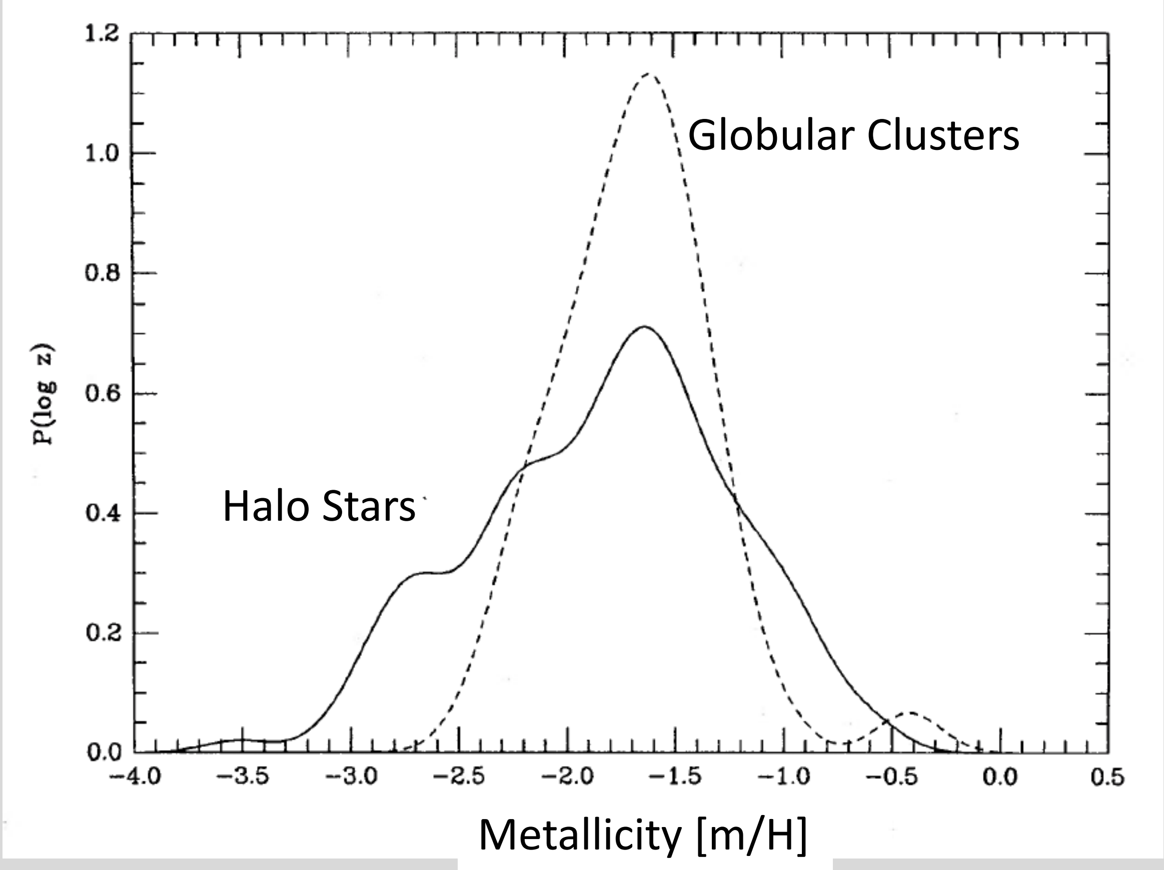
High proper motion stars [(Carney+ 96)]

Halo stars show a broader range of metallicity than globular clusters.

The most metal-poor halo stars known today have [Fe/H] < −5, and often show very strange elemental abundance ratios. ⇒ tracers of the earliest phase of chemical enrichment.



The stellar halo: Smooth versus Accreted

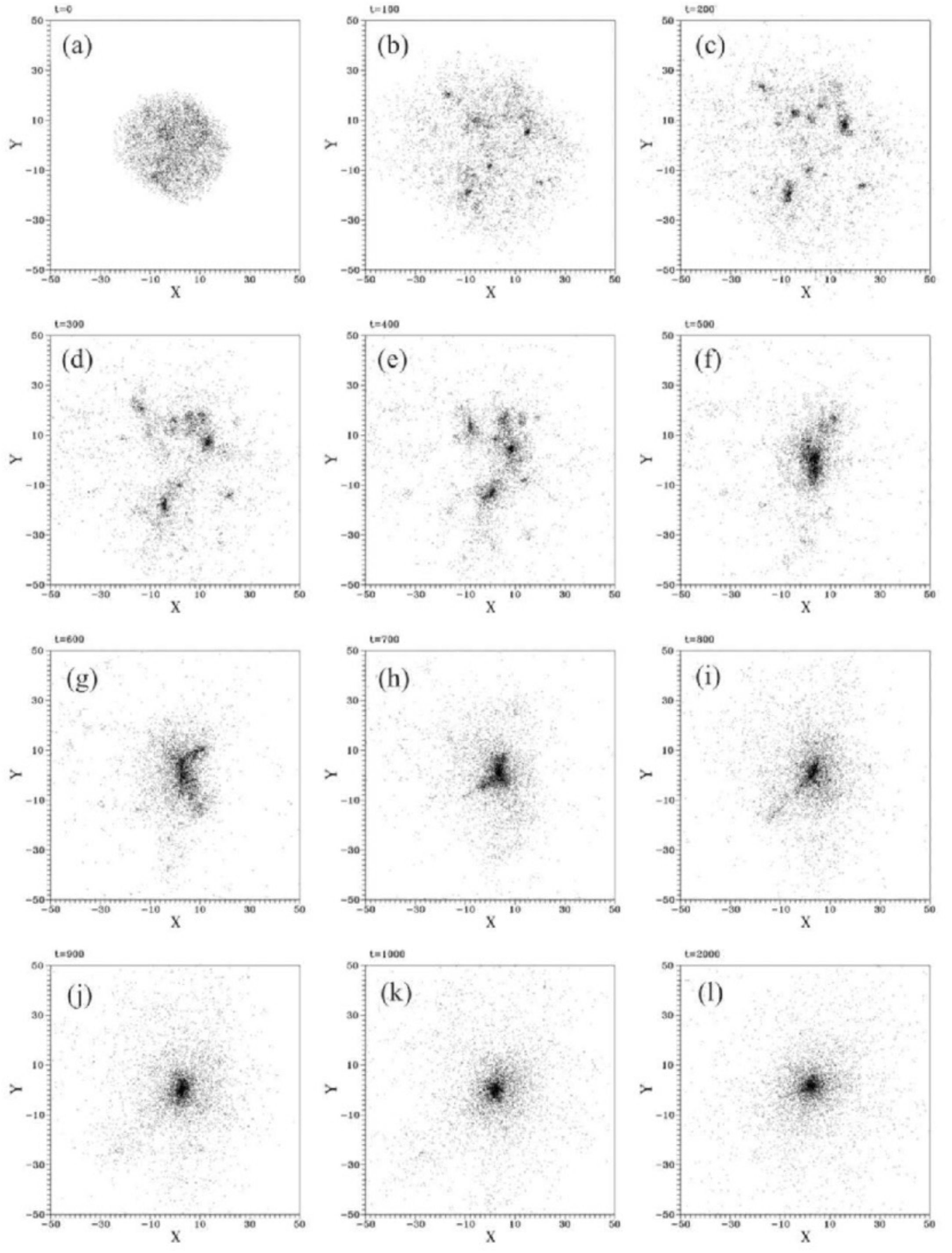
Original view was that the galaxy formed in a smooth contraction of primordial gas (Eggen, Lynden-Bell, & Sandage 1962, aka ELS, or monolithic collapse), and the halo should be smooth as well.

A somewhat more realistic version might look like this ⇒

Early rapid formation of halo, followed by subsequent cooling and settling of gas into a disk.

Halo formation marked by **violent relaxation**: Rapid merger of comparable-mass things: gravitational potential changes rapidly, stars are scattered off their orbits forming a smooth and kinematically hot component.

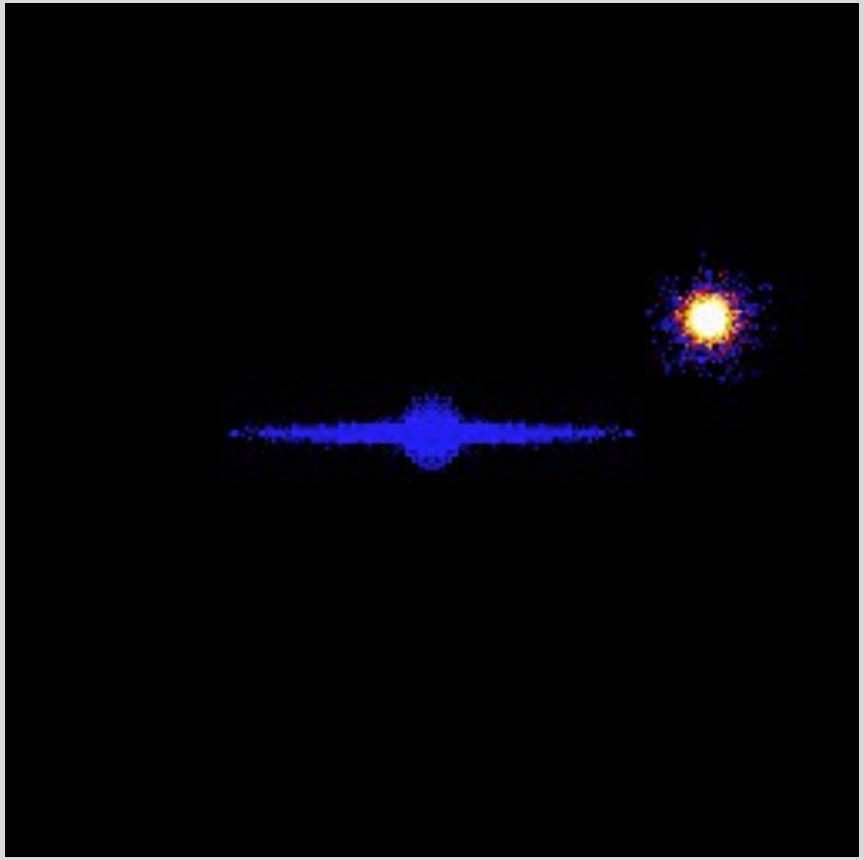
Kalapotharakos 06



The stellar halo: Smooth versus Accreted

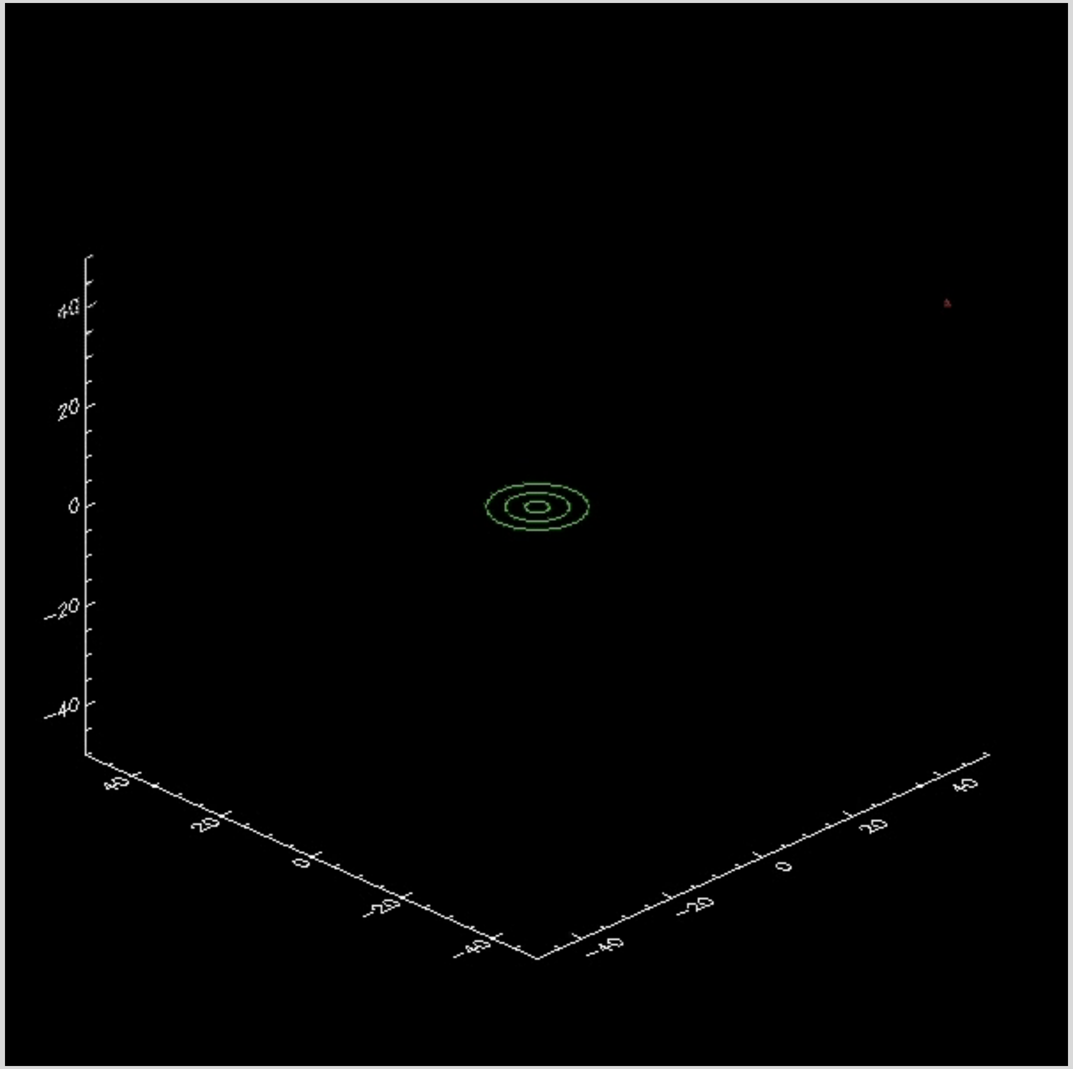
But as hierarchical galaxy formation models gained traction, an alternative view rose: the accreted stellar halo (Searle & Zinn 1978, aka SZ, or hierarchical accretion)

Single accretion



courtesy Kathryn Johnston

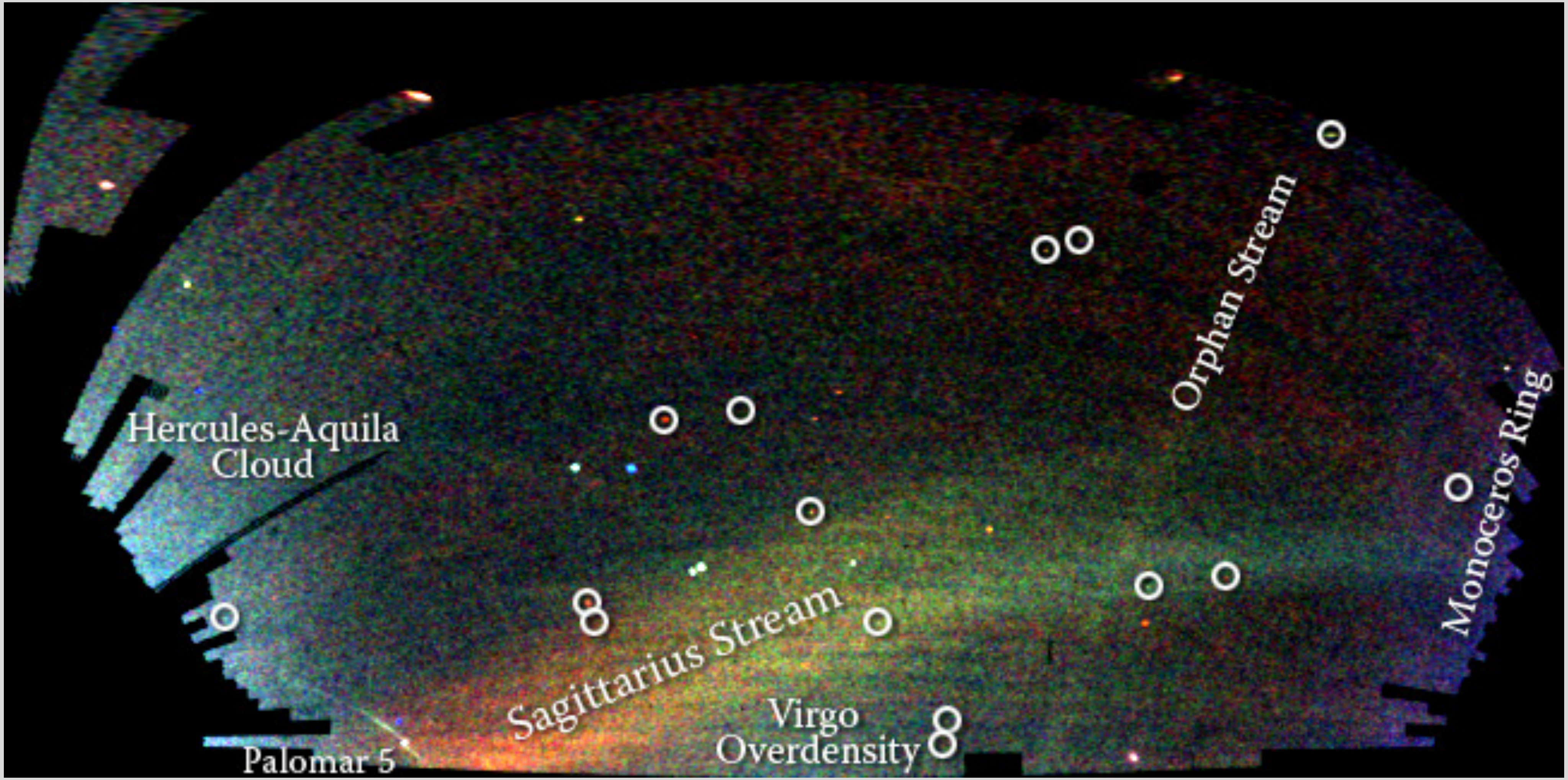
Multiple events



Johnston & Bullock

Accretion signatures: The Field of Streams

Belokurov+ 06: Select SDSS stars on color: $g - r \approx 0.4$. These would be main sequence turnoff stars with roughly similar absolute mags, so apparent mag is a rough estimate of distance. Color code by distance: blue⇒near, red⇒far



Accretion signatures: Multiple tracers

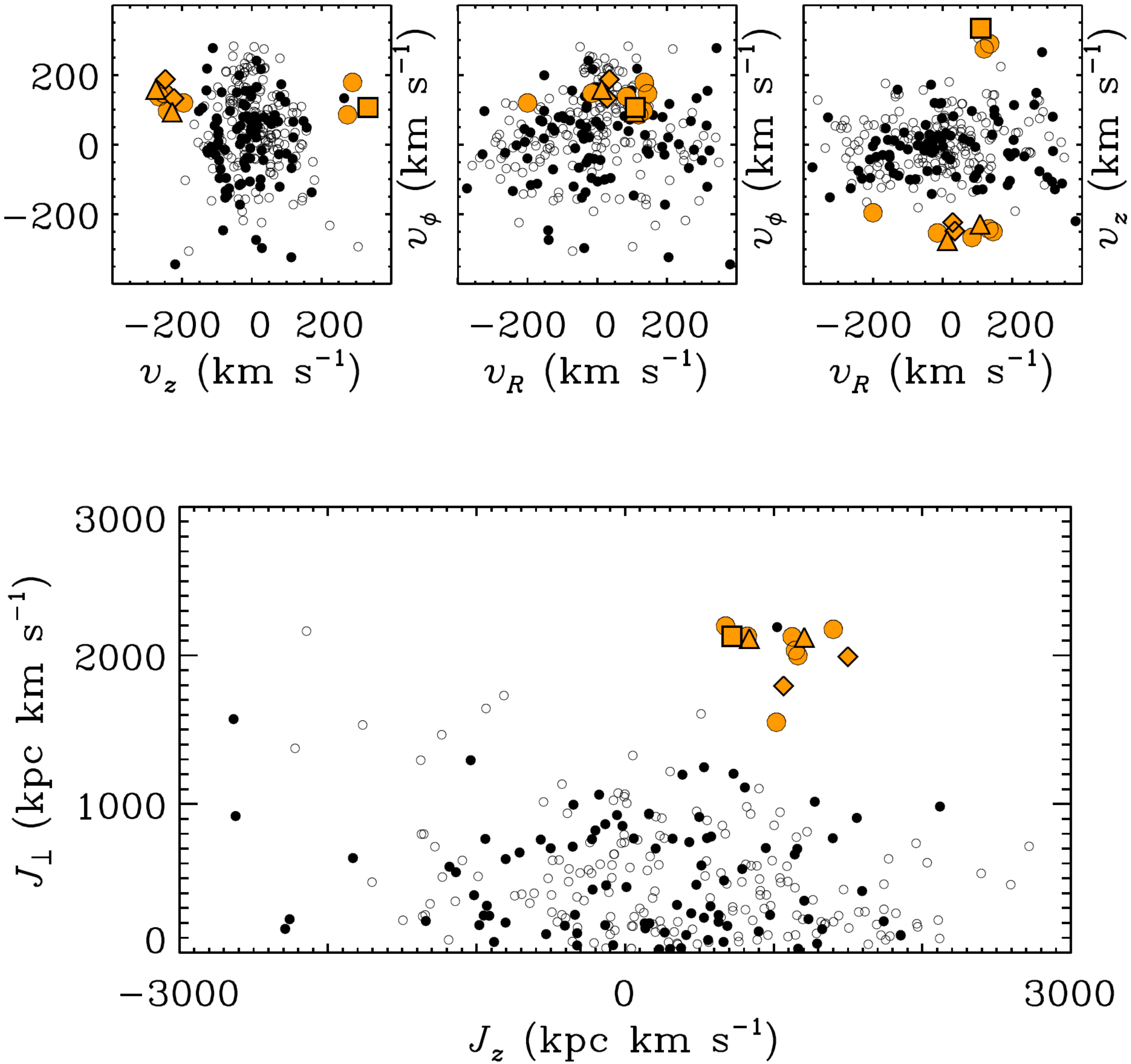
If the Galactic potential isn't changing much, even though stars will diffuse along the stream over time, they will conserve energy and angular momentum and remain kinematically correlated.

Helmi+ 99: Kinematics of nearby (<1 kpc) metal-poor RR Lyrae stars.

Find a discrete clump in

- velocity v_z, v_r, v_ϕ
- angular momentum ($J_\perp$, J_z)

NOT SMOOTH!



Accretion signatures: Multiple tracers

Modern view: A little bit of everything.

- **“in-situ halo”:** Early formation history probably leads to violent relaxation and formation of a smooth inner halo population.
- **“accreted halo”:** Subsequent accretion builds up the outer halo through disrupted satellites

Current arguments center on the fraction of in-situ vs accreted halo, and how that changes with Galactic radius.

With bigger samples of halo stars and more data, we can search for halo substructure using many tracers: position (X,Y,Z) velocity (vx, vy, vz), energy and angular momentum (E, L), metallicity ([Fe/H], [α/Fe]), etc.

Important to remember: the ages and metallicities of stars in accretion streams do not tell us about when they fell in to the halo, but when they were formed within their satellite. A stream from a satellite that fell in yesterday can easily have old stars!