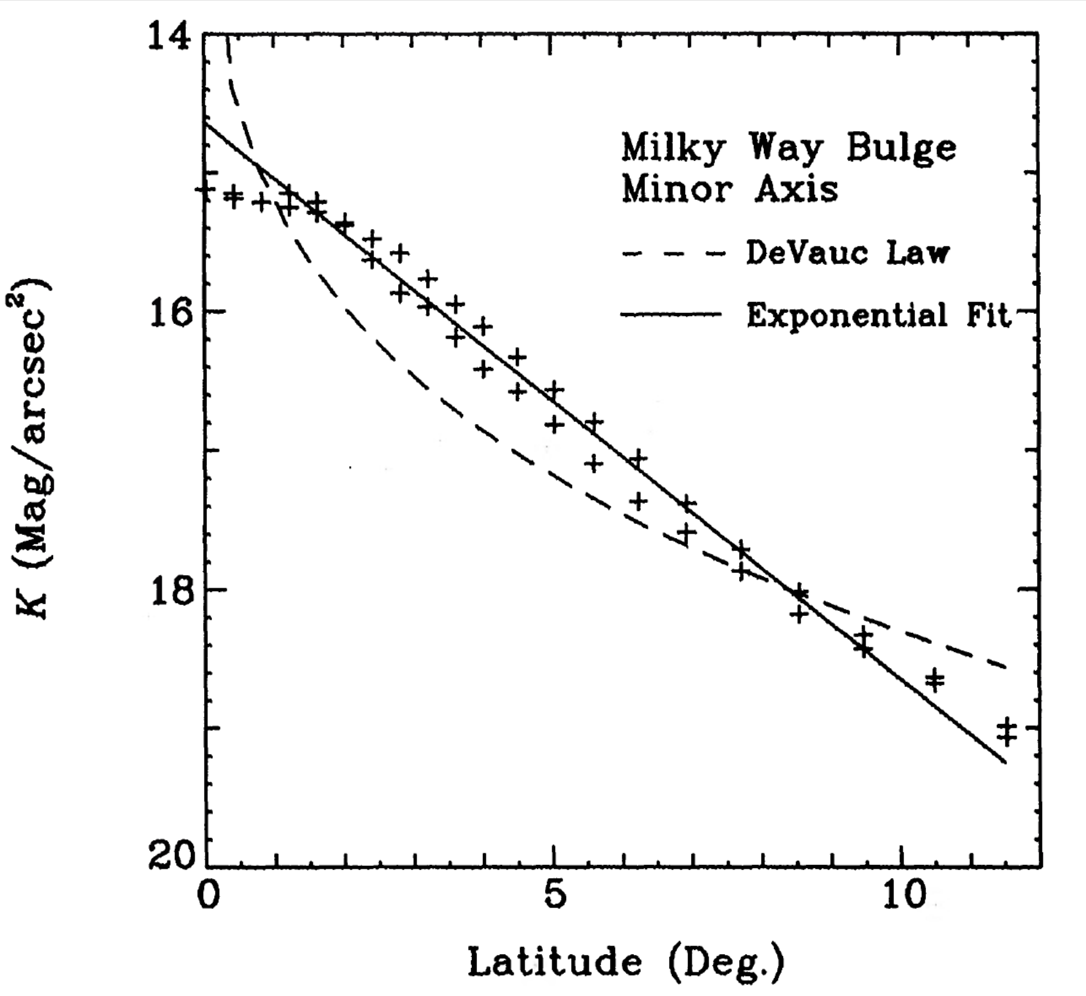
The Milky Way’s Bulge

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.

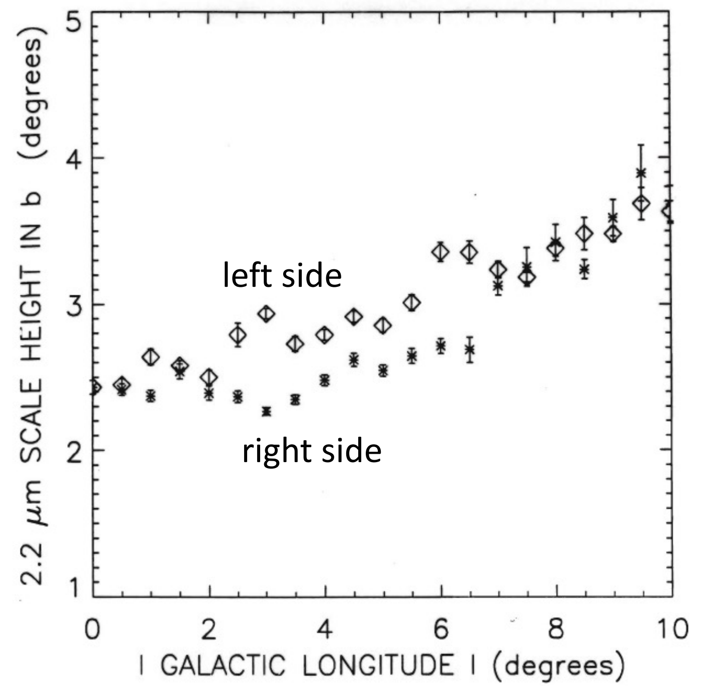
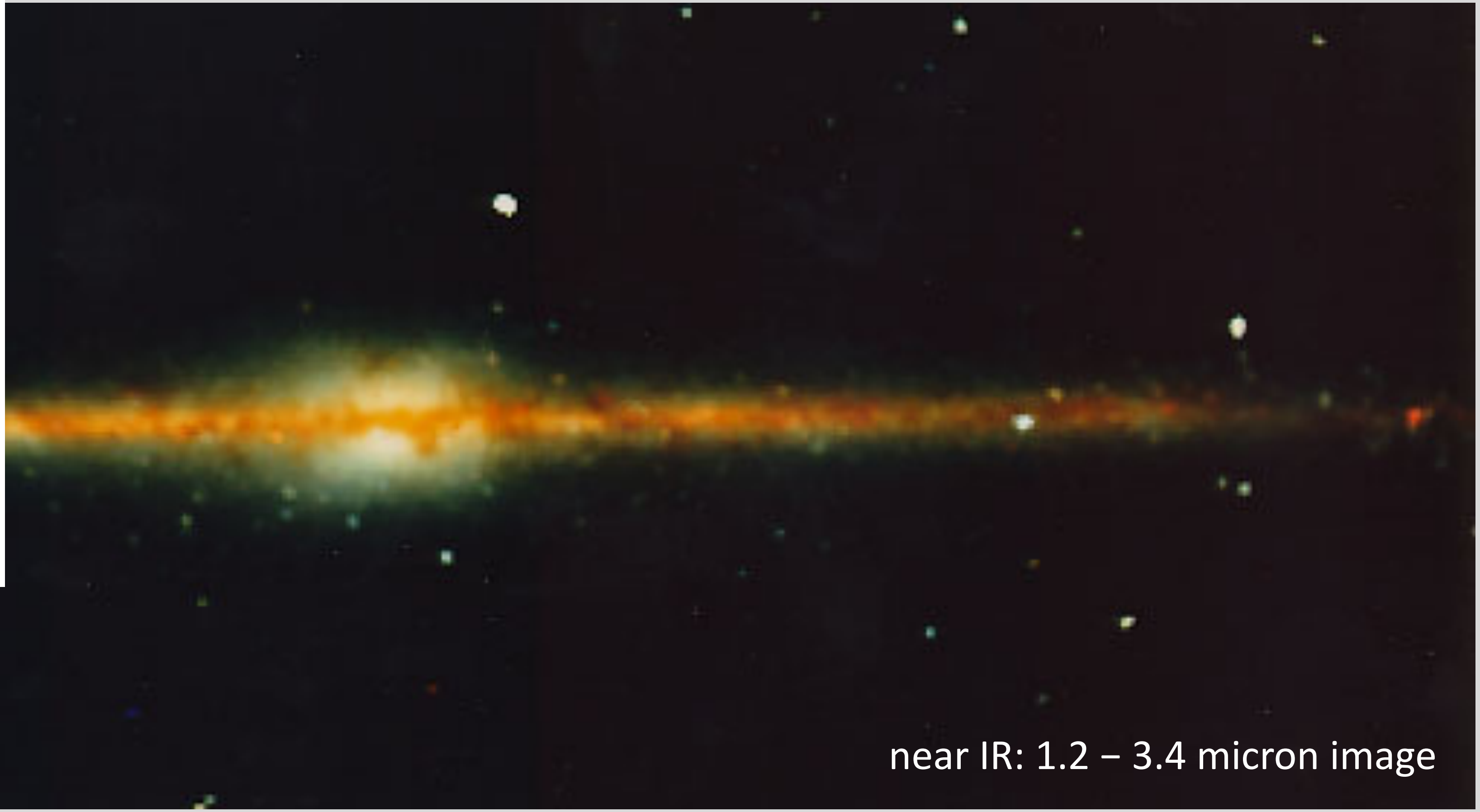


FIG. 2.—2.2 μm angular scale heights at fixed longitude. Scale heights for $l < 0°$ are represented by asterisks, whereas diamonds are for scale heights at positive Galactic longitudes. The error bars represent 1 σ errors on the computed scale height.

⇐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.

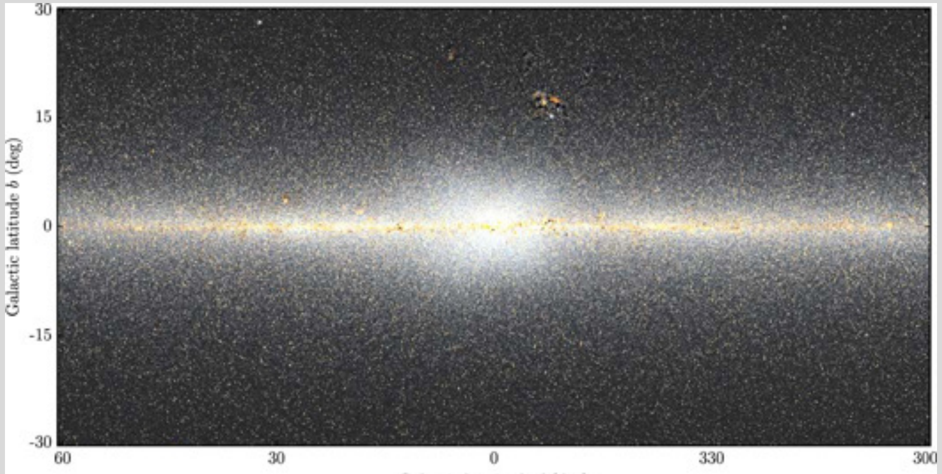


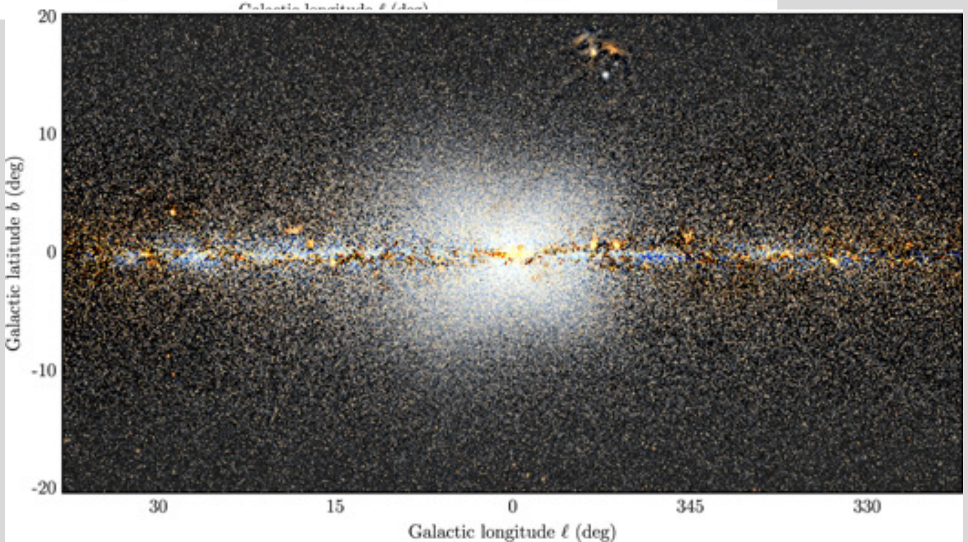
near IR: 1.2 – 3.4 micron image

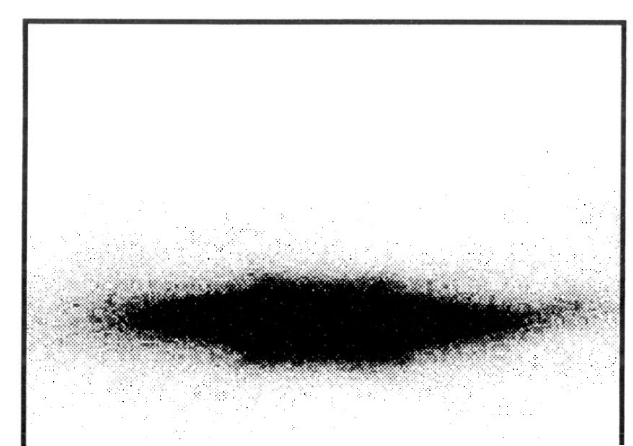
The Milky Way's Bar

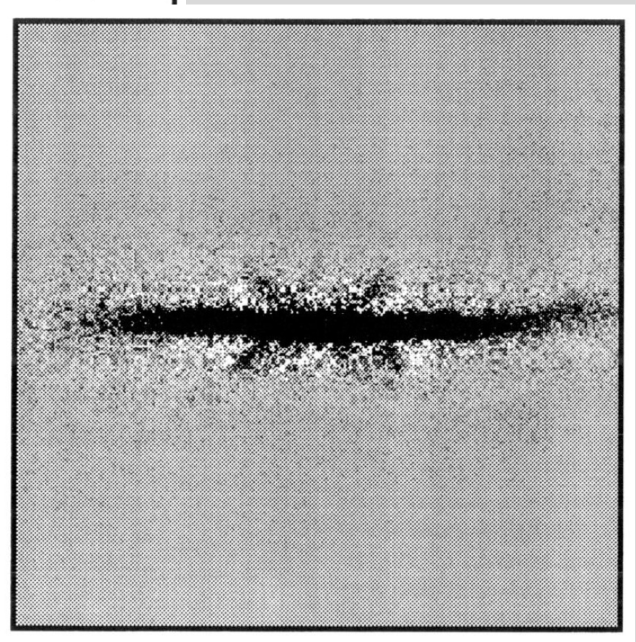
Bars are a natural dynamical instability in rotating disks. They buckle vertically, giving the impression of a peanut-shaped or X-shaped bulge.

WISE near-IR imaging (Ness & Lang 16)









Barred galaxy simulation (Mihos+ 95)

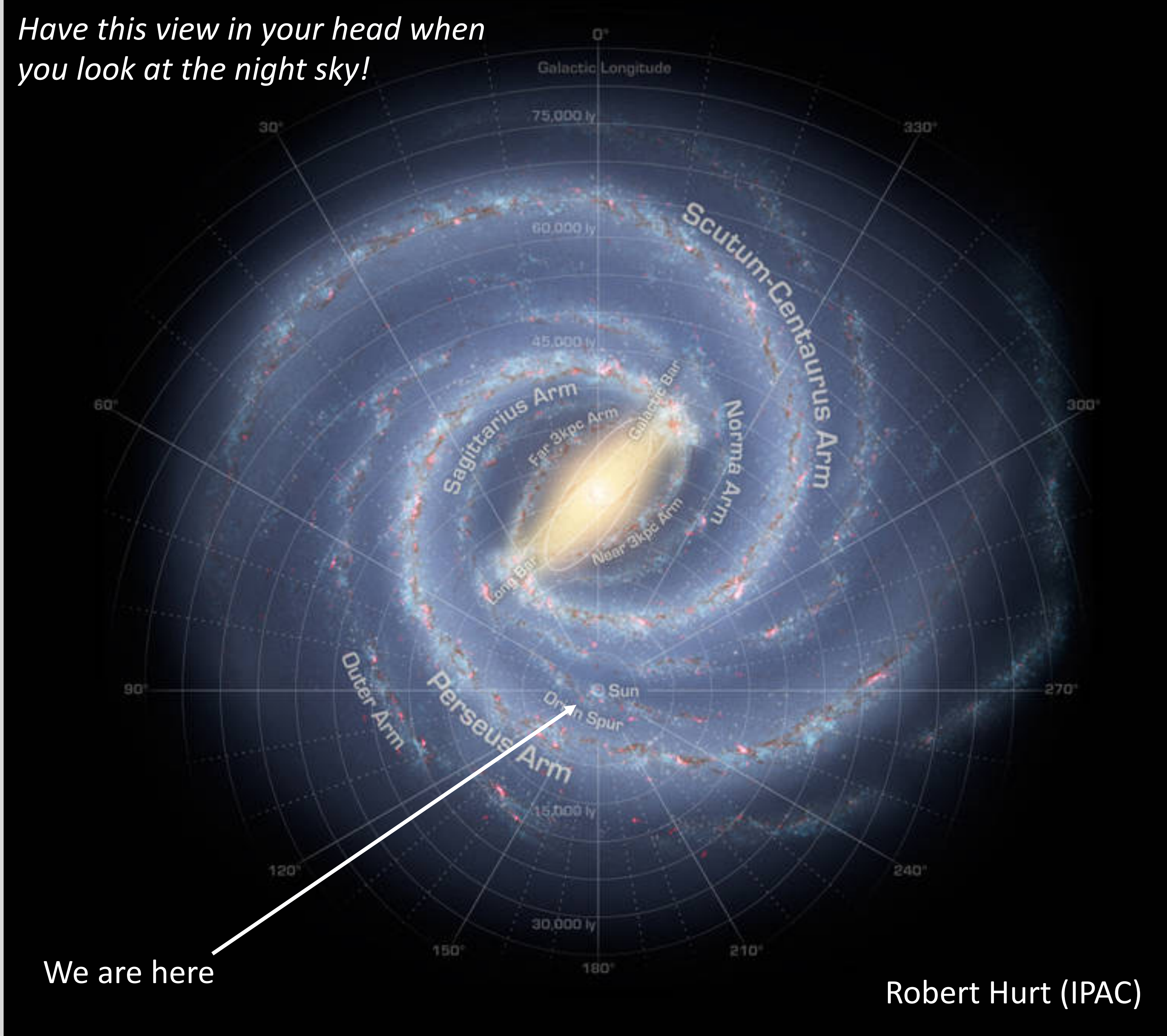
YouTube animations of bar instabilities:

- 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….



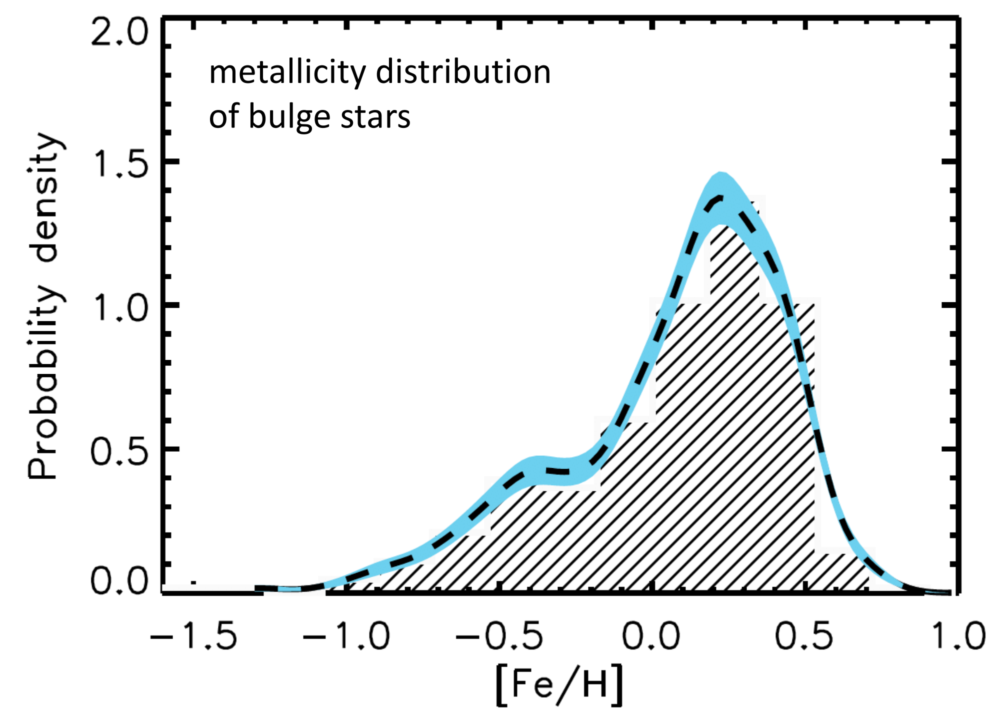
Have this view in your head when you look at the night sky!

We are here

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.

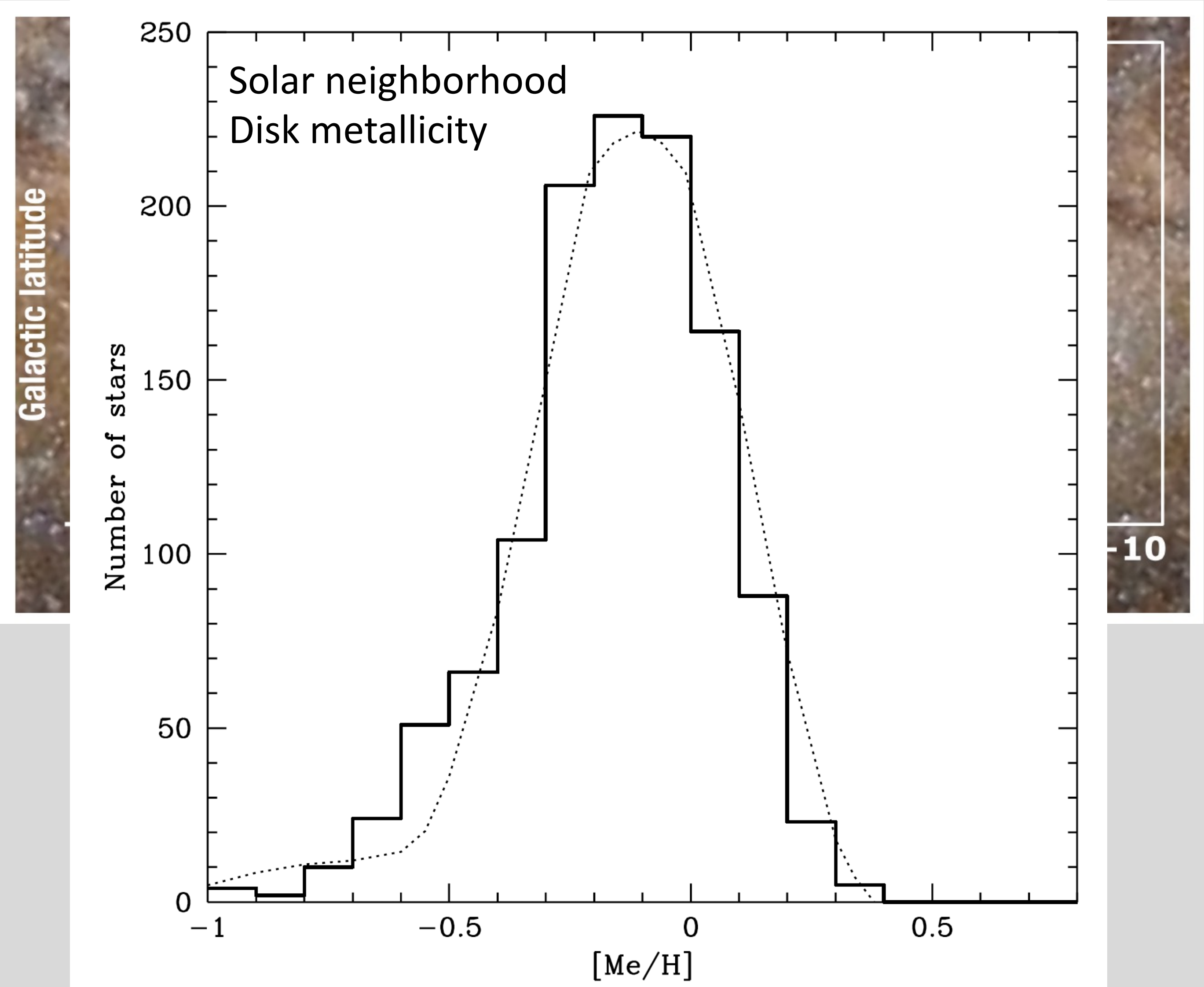
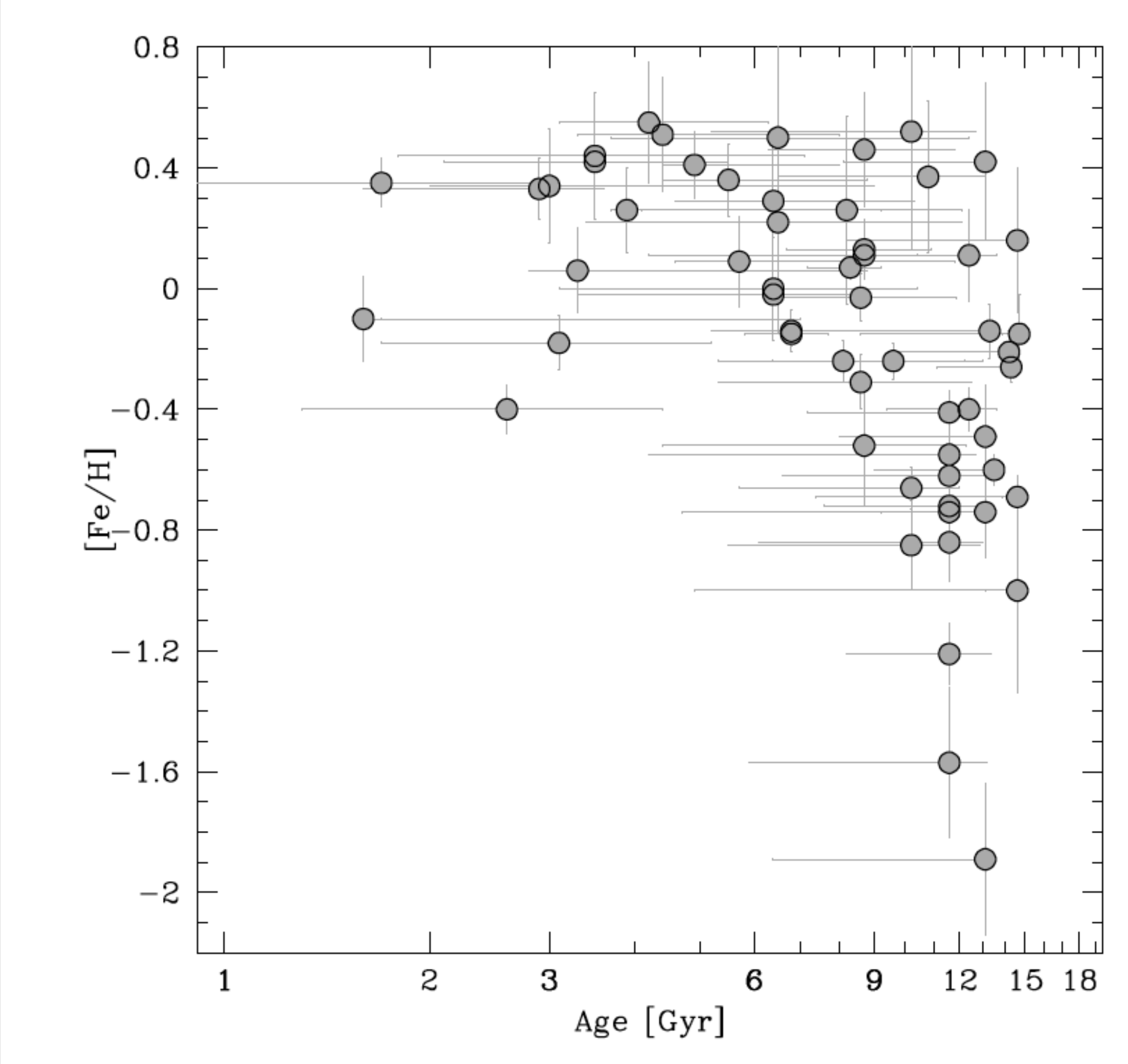


Fig. 26. Distribution of metallicities for the volume complete sample of single stars (full histogram). For comparison the dotted curve shows the reconstructed distribution for G dwarfs from Jørgensen (2000), which is corrected for scale height effects and measurement errors.

Age Distribution in Bulge/Bar/InnerDisk

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

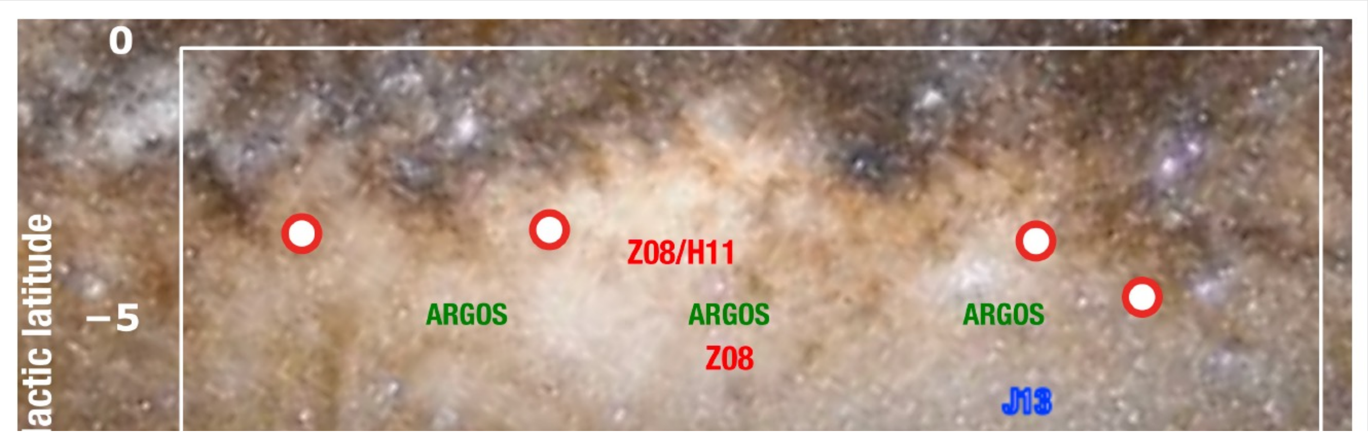
Many of the oldest stars have high metallicity: *Metallicity enrichment can happen fast.*

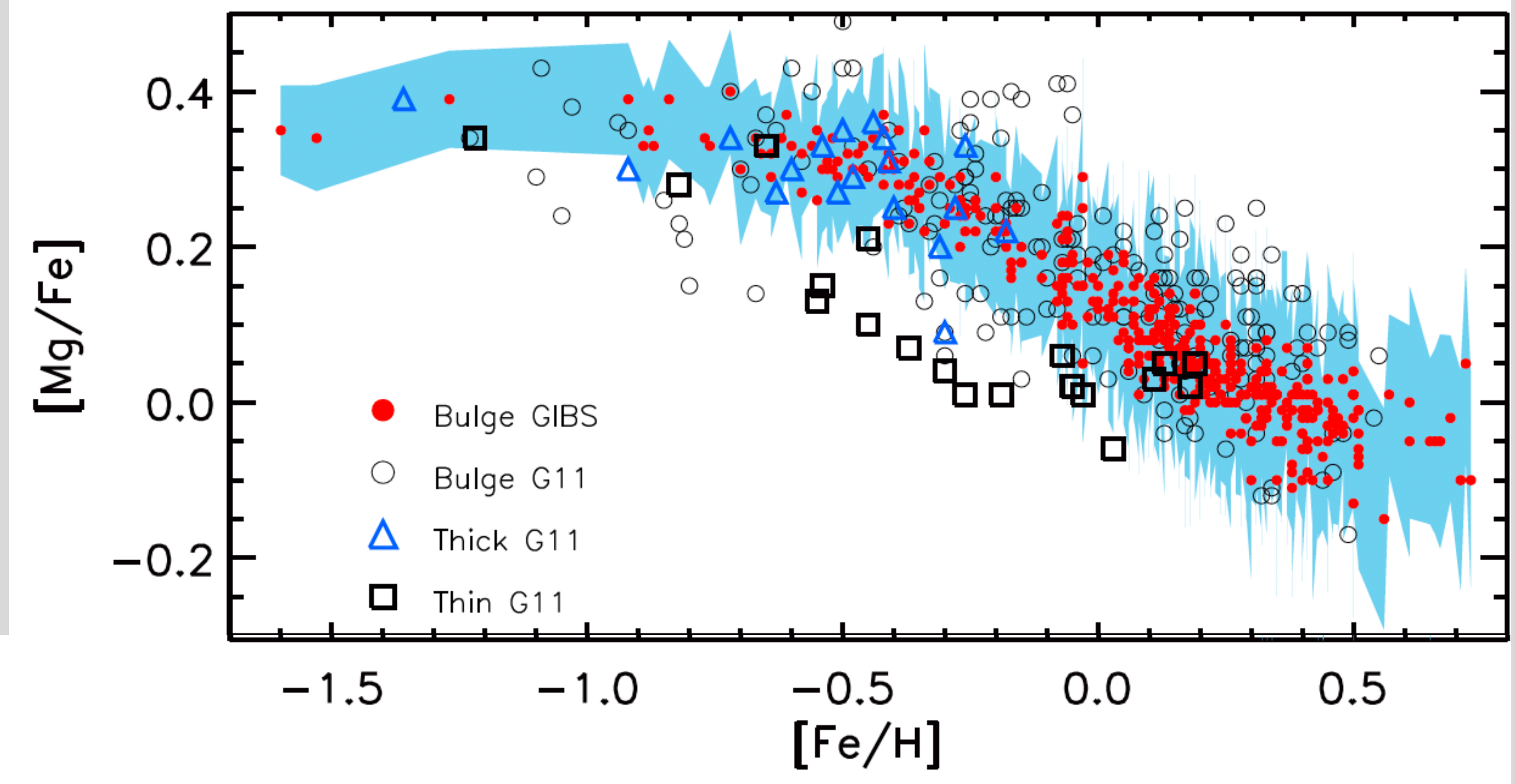


Bensby+13

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”

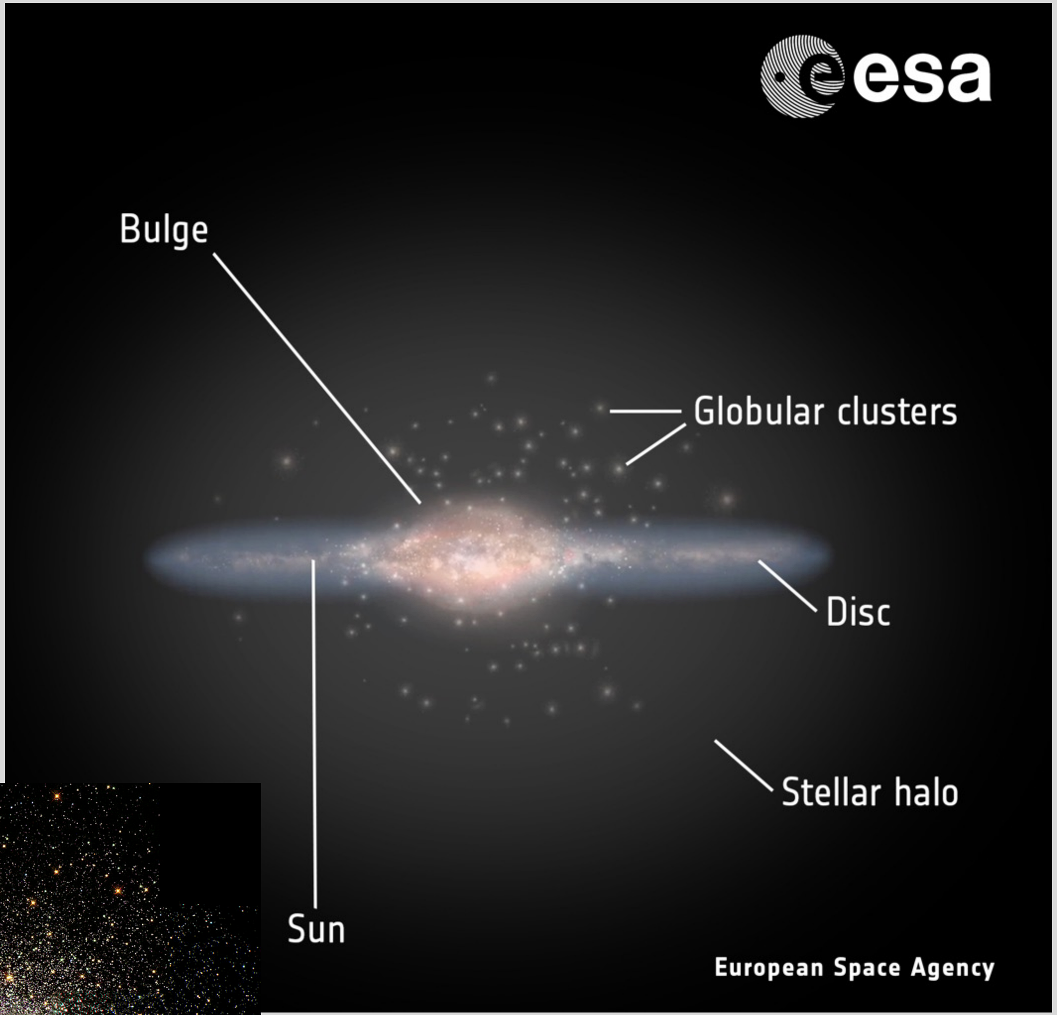
The Milky Way's Stellar Halo

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.



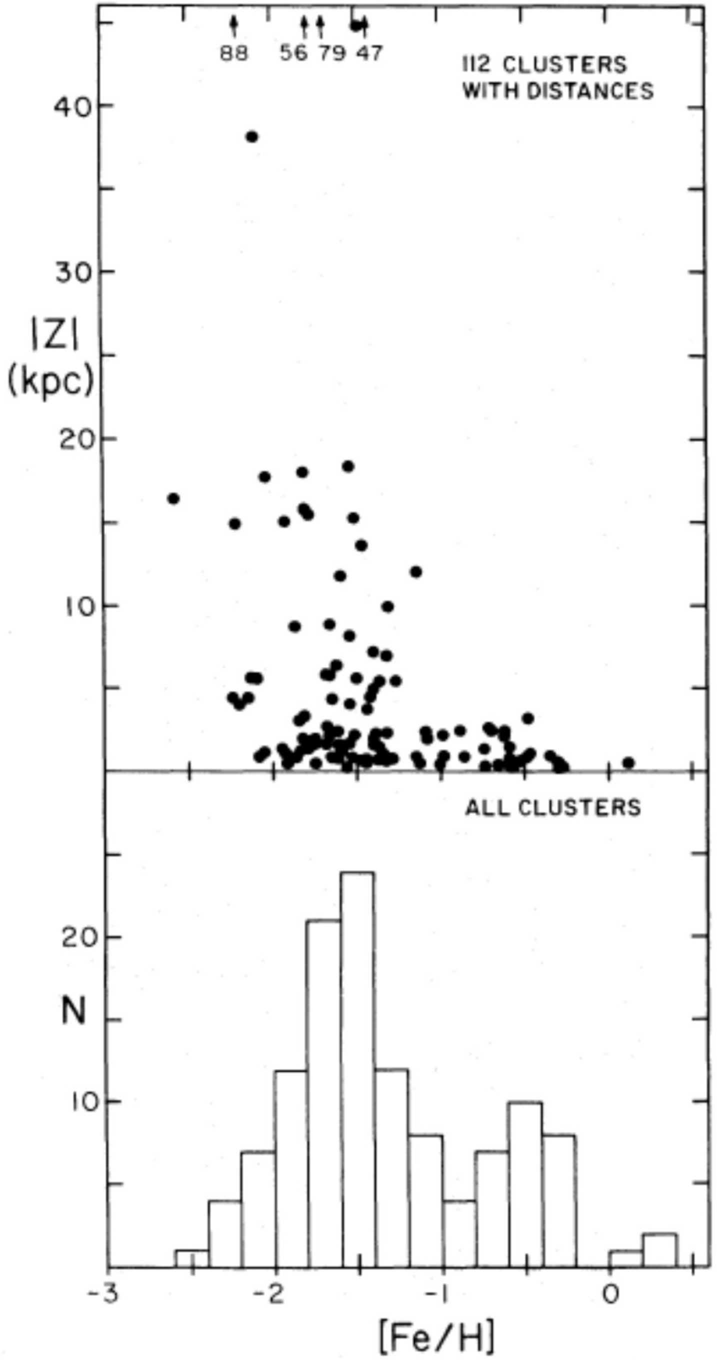
Studying the Stellar Halo: Globular Clusters

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

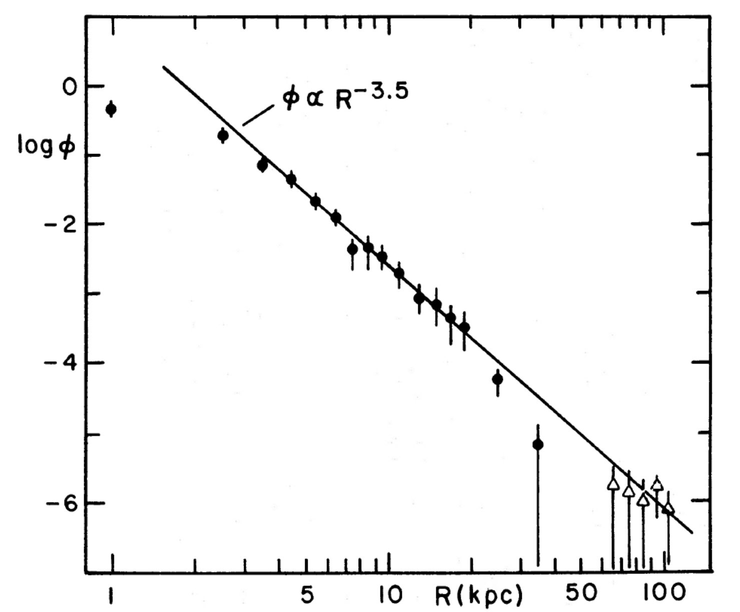
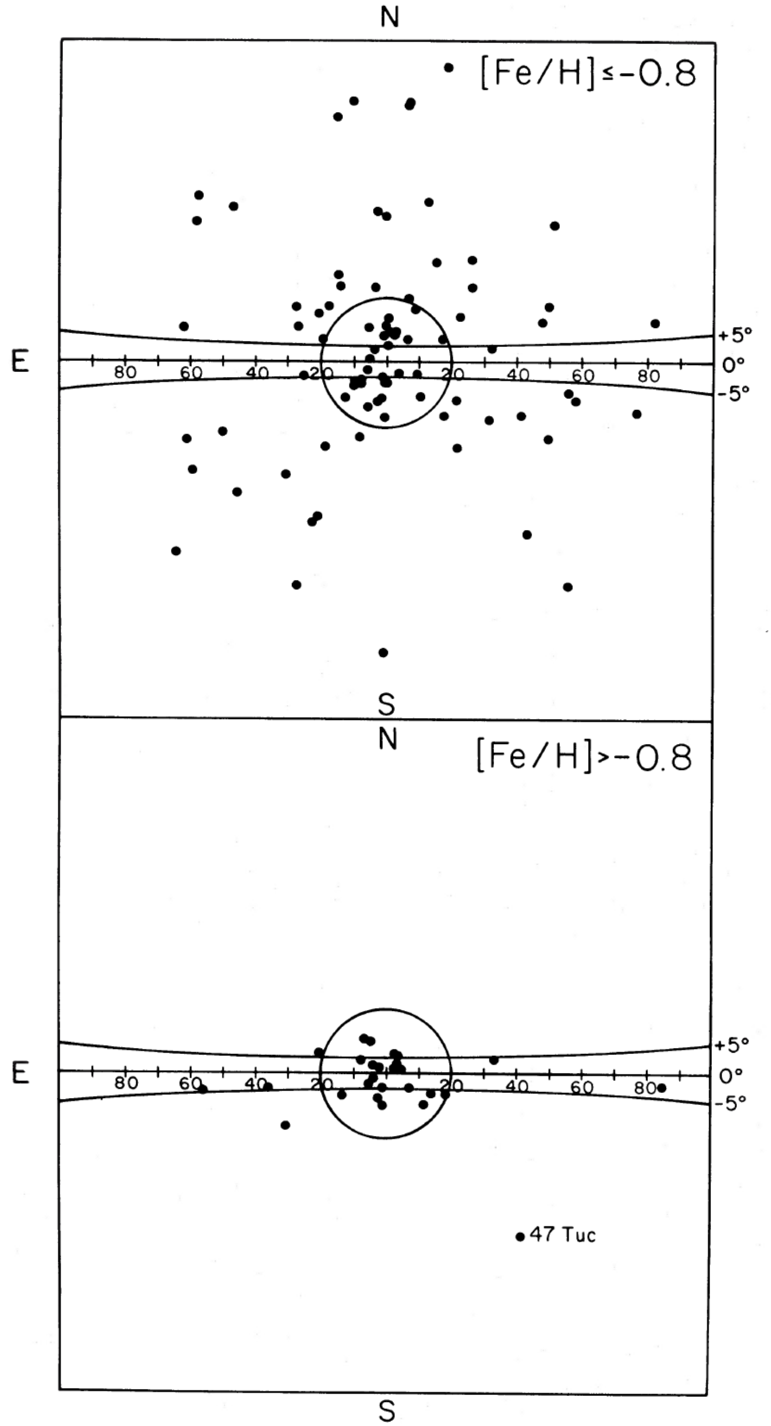


FIG. 2.—The number of clusters per cubic kiloparsec (ϕ) is plotted against galactocentric distance (R). The solid circles represent the clusters with $|Z| < 20$ kpc; the open triangles represent the clusters with $|Z| > 37$ kpc. There are no clusters in the zone $33 < R < 60$ kpc.

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.

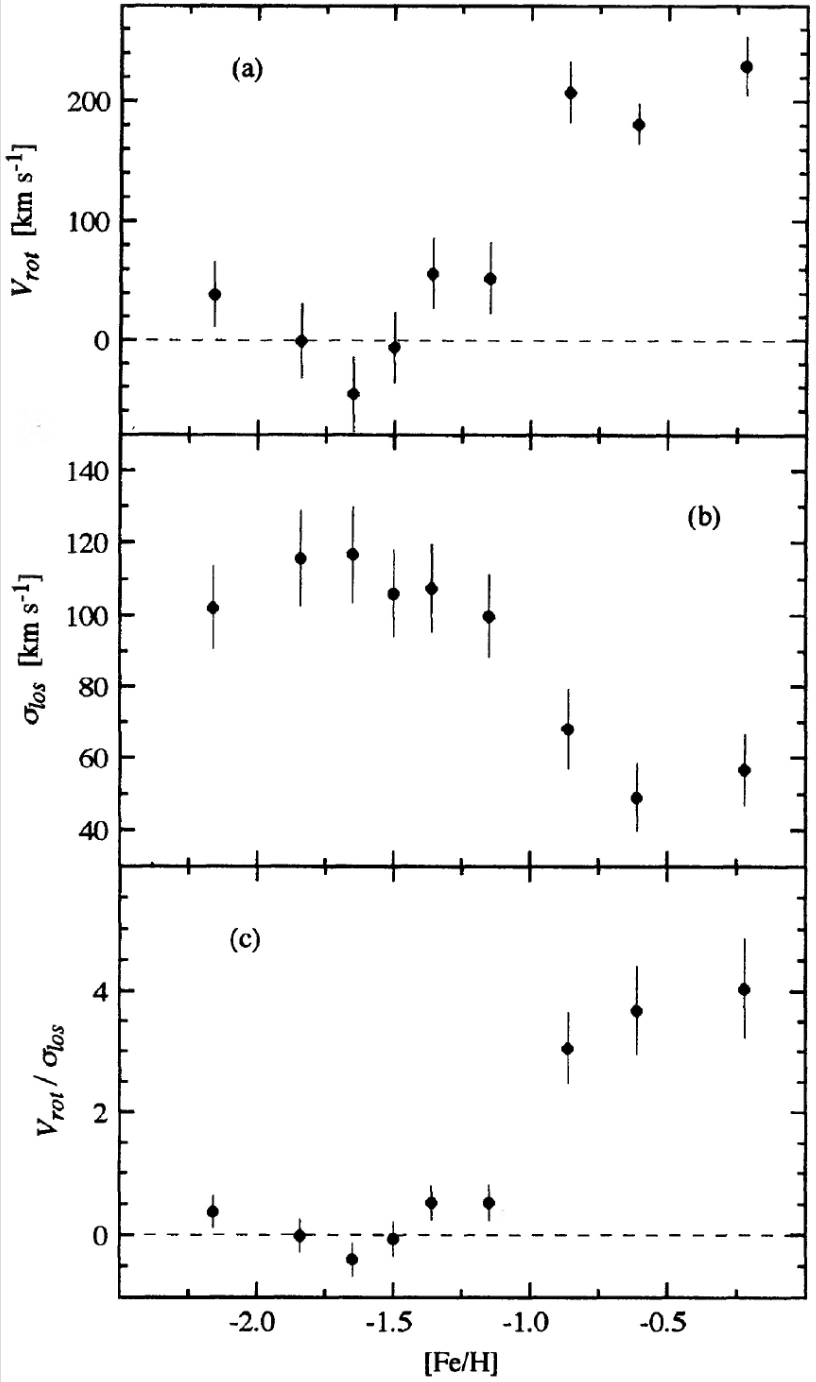
Layden (1995): Nearby (d<2.5 kpc) RR Lyraes

−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

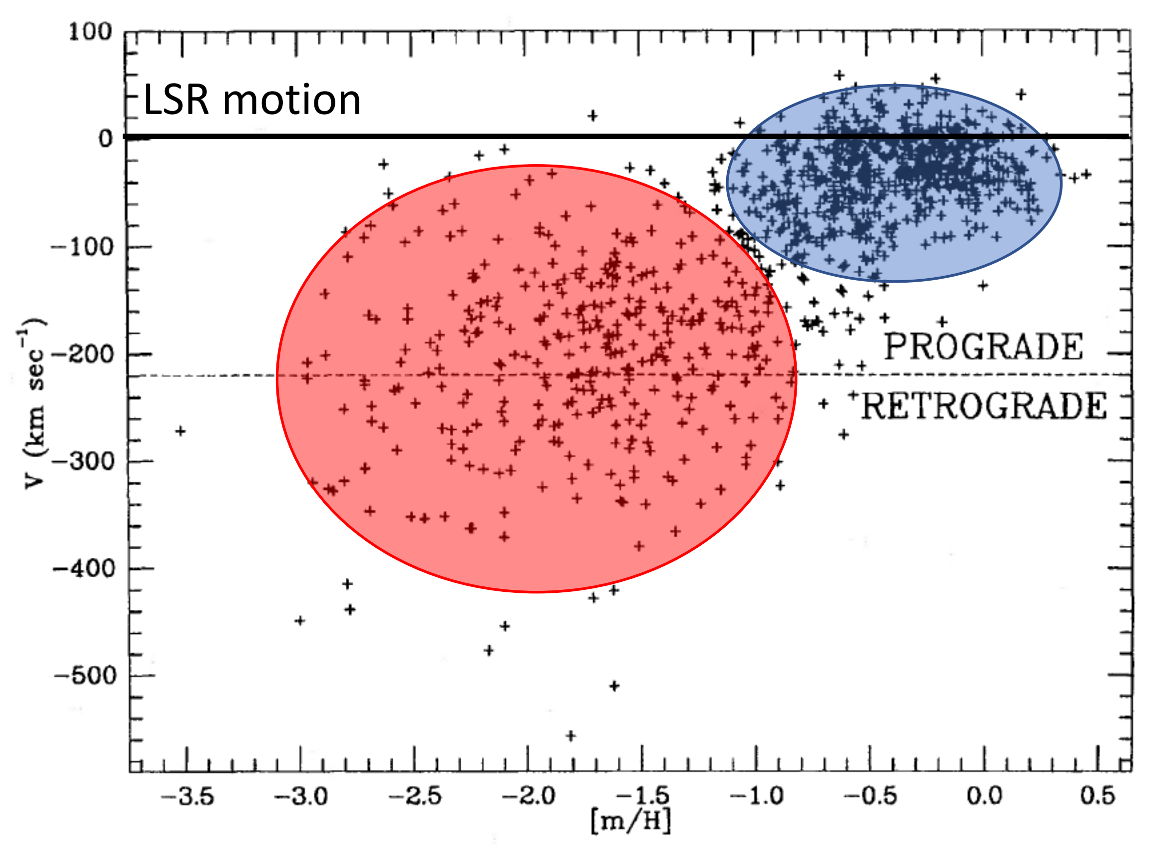
Advantage: Greater numbers (selecting all stars, not just a specific evolutionary type)
Disadvantage: Need to disentangle from disk population. halo:disk ratio is 1:1000. How?

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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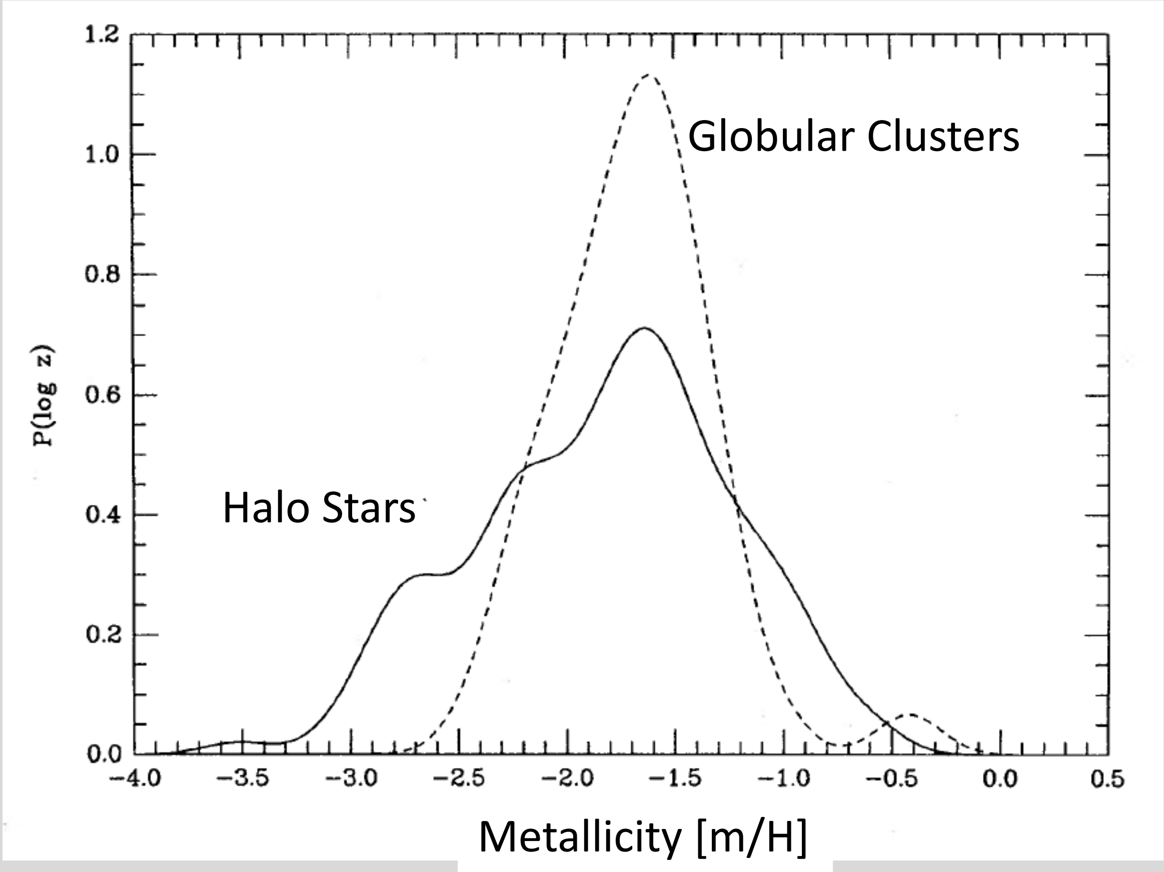
High proper motion stars (Carney+ 96)

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.



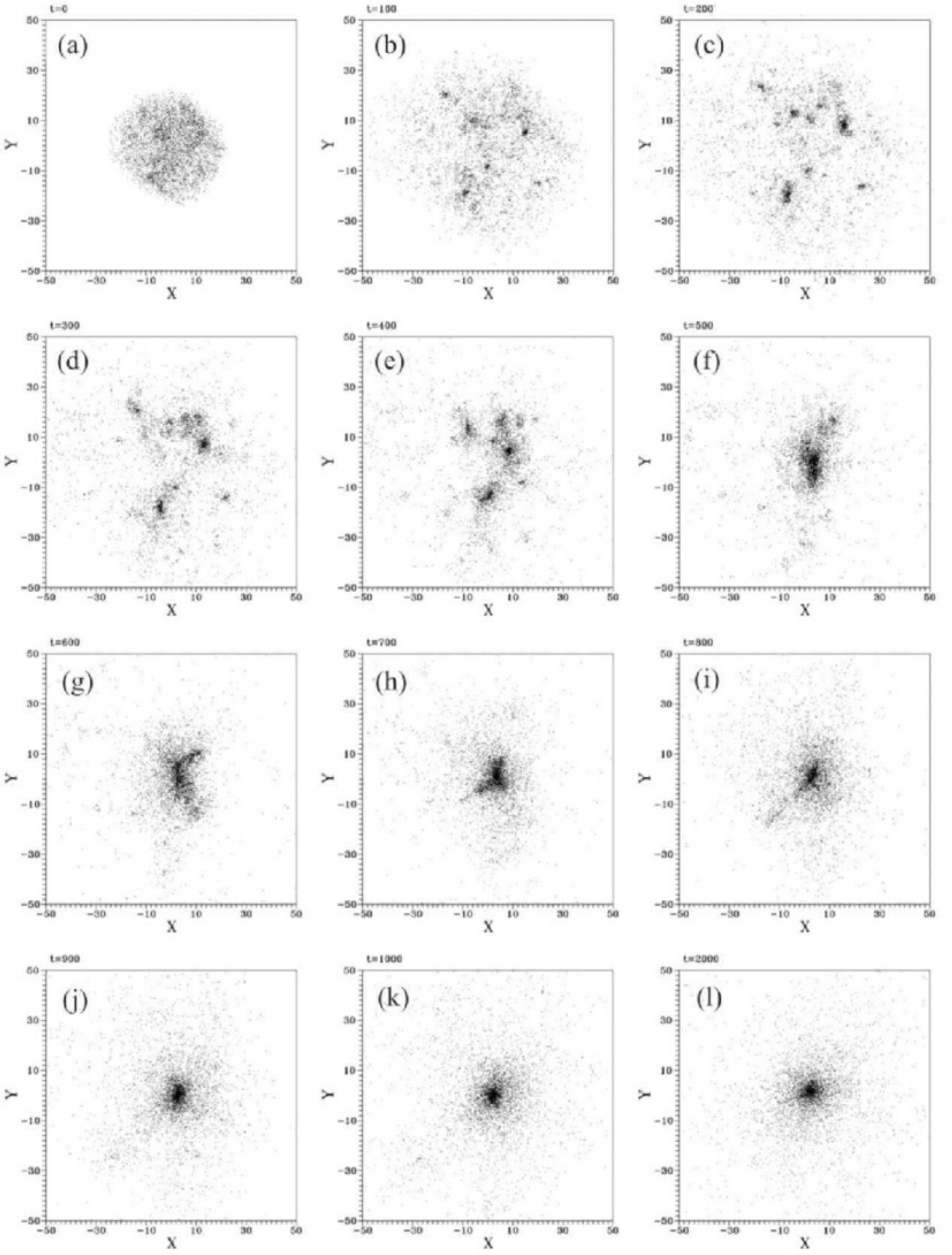
The stellar halo: Smooth versus Accreted

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.

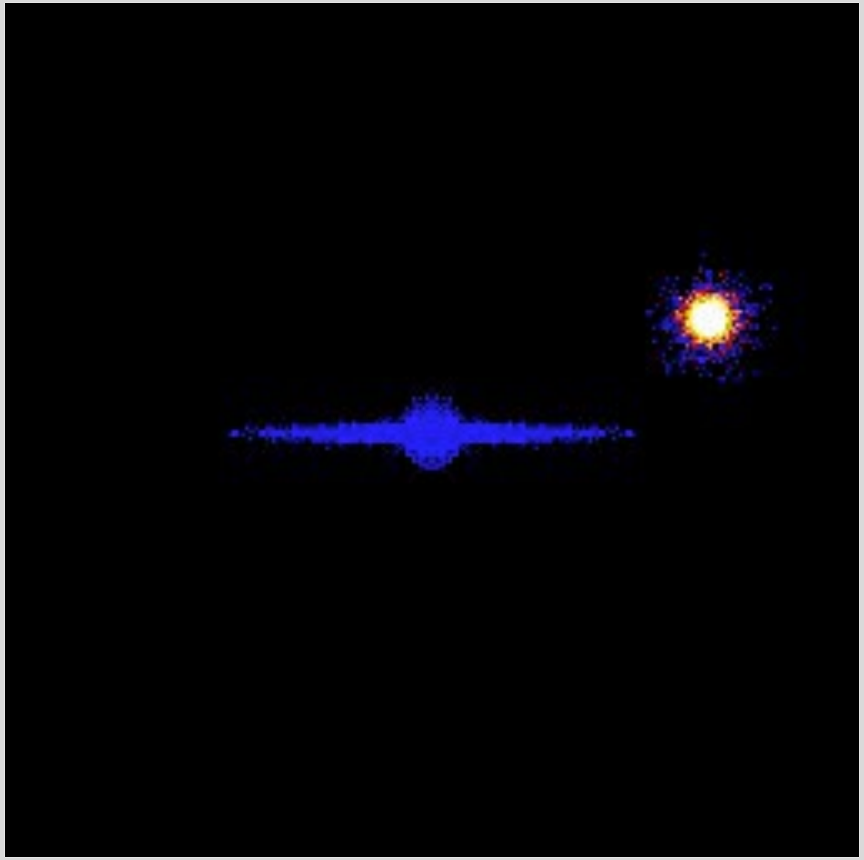


Kalapotharakos 06

The stellar halo: Smooth versus Accreted

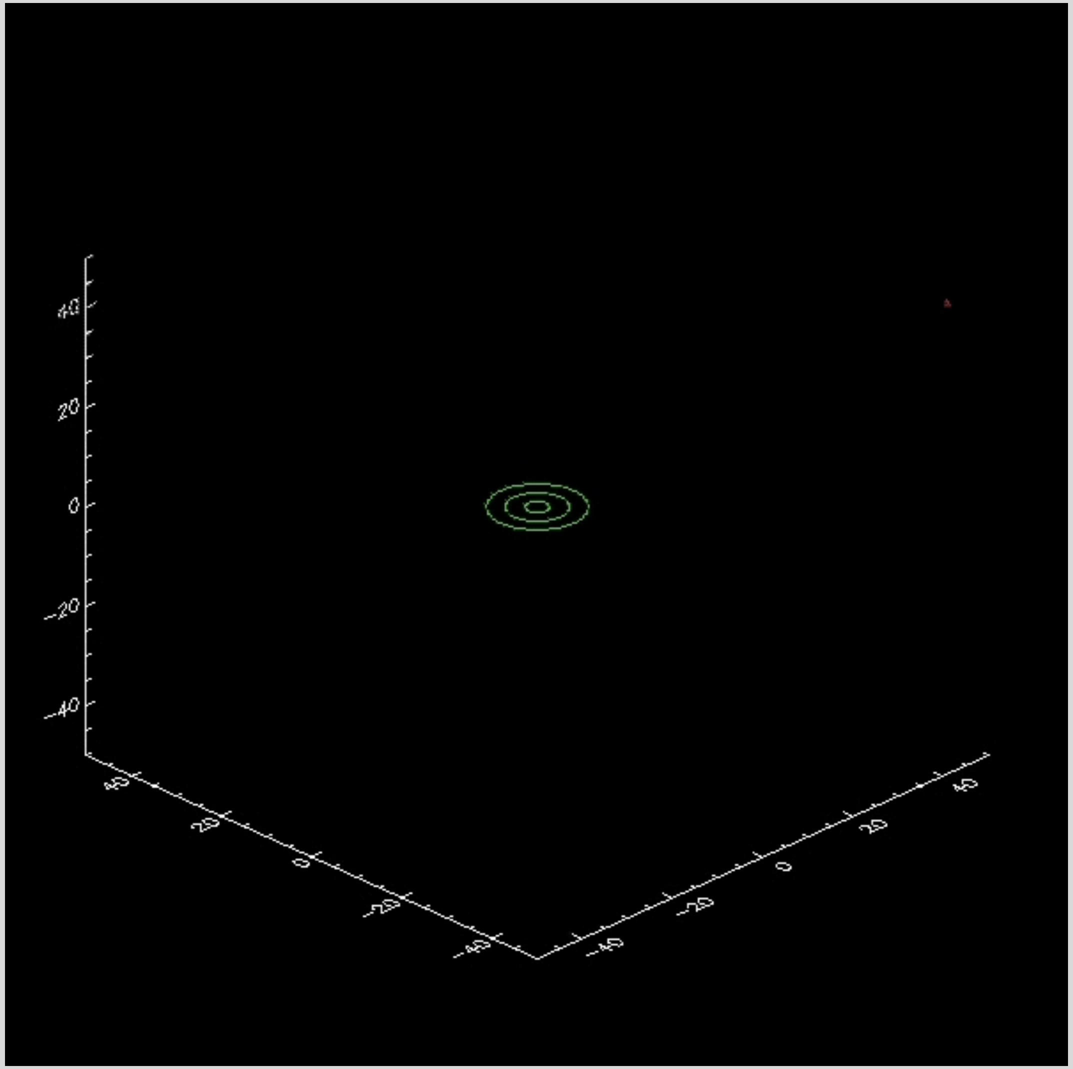
But as hierarchical galaxy formation models gained traction, an alternative view rose: the accreted stellar halo (Searle & Zinn 1978, aka SZ, or hierarchical accretion)

Single accretion



courtesy Kathryn Johnston

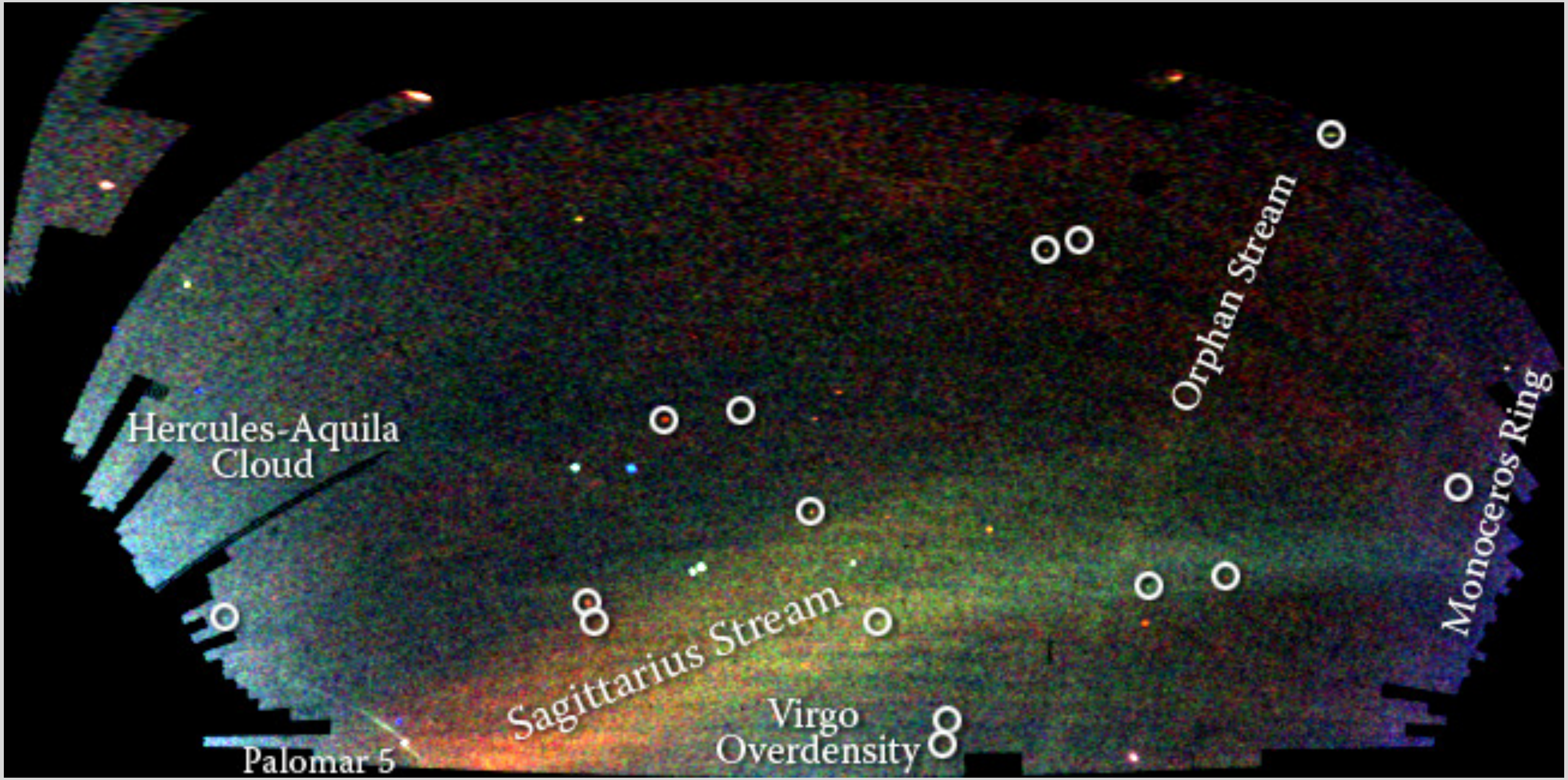
Multiple events



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

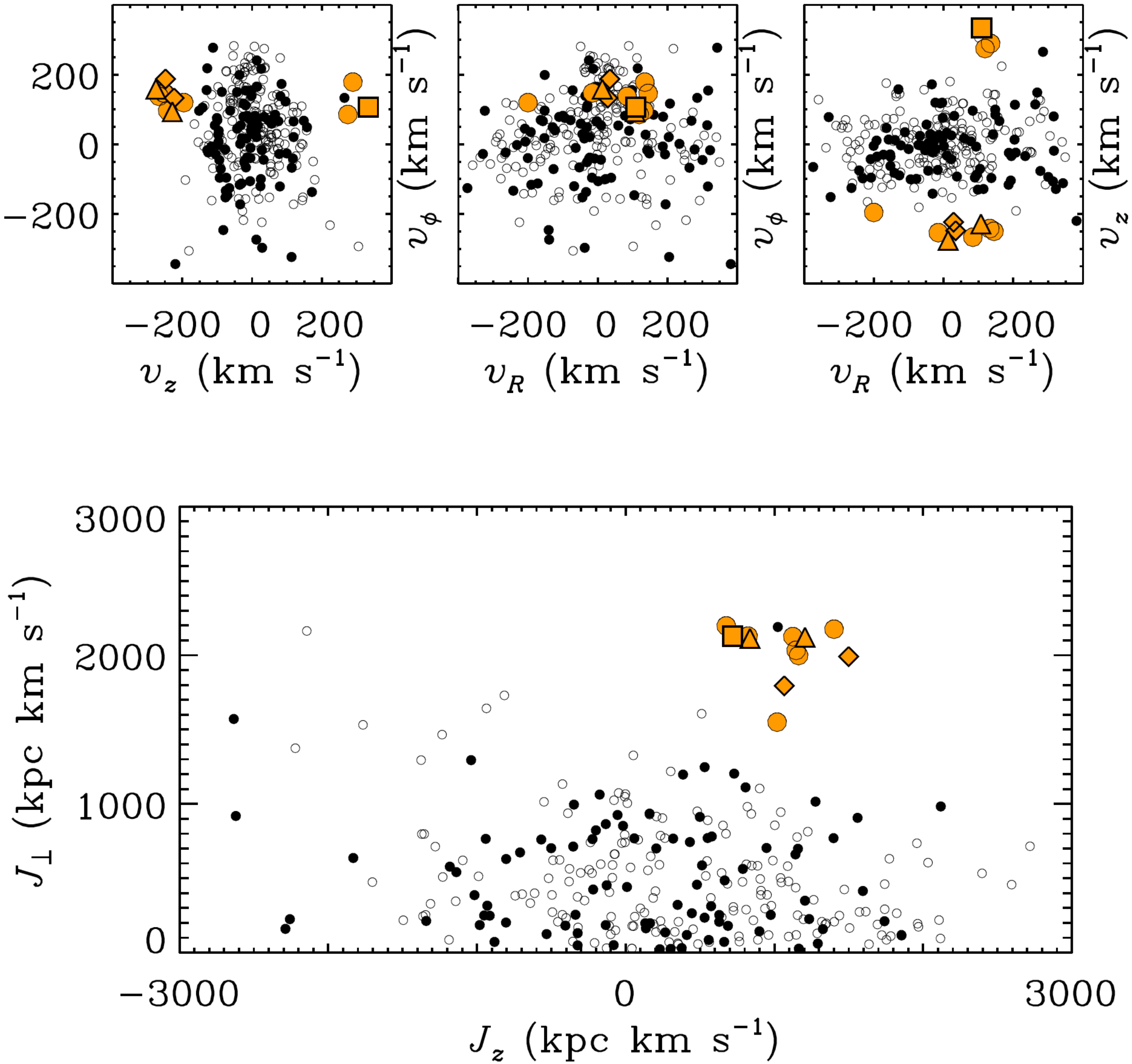
If the Galactic potential isn't changing much, even though stars will diffuse along the stream over time, they will conserve energy and angular momentum and remain kinematically correlated.

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!