Astr 511: Galaxies as galaxies

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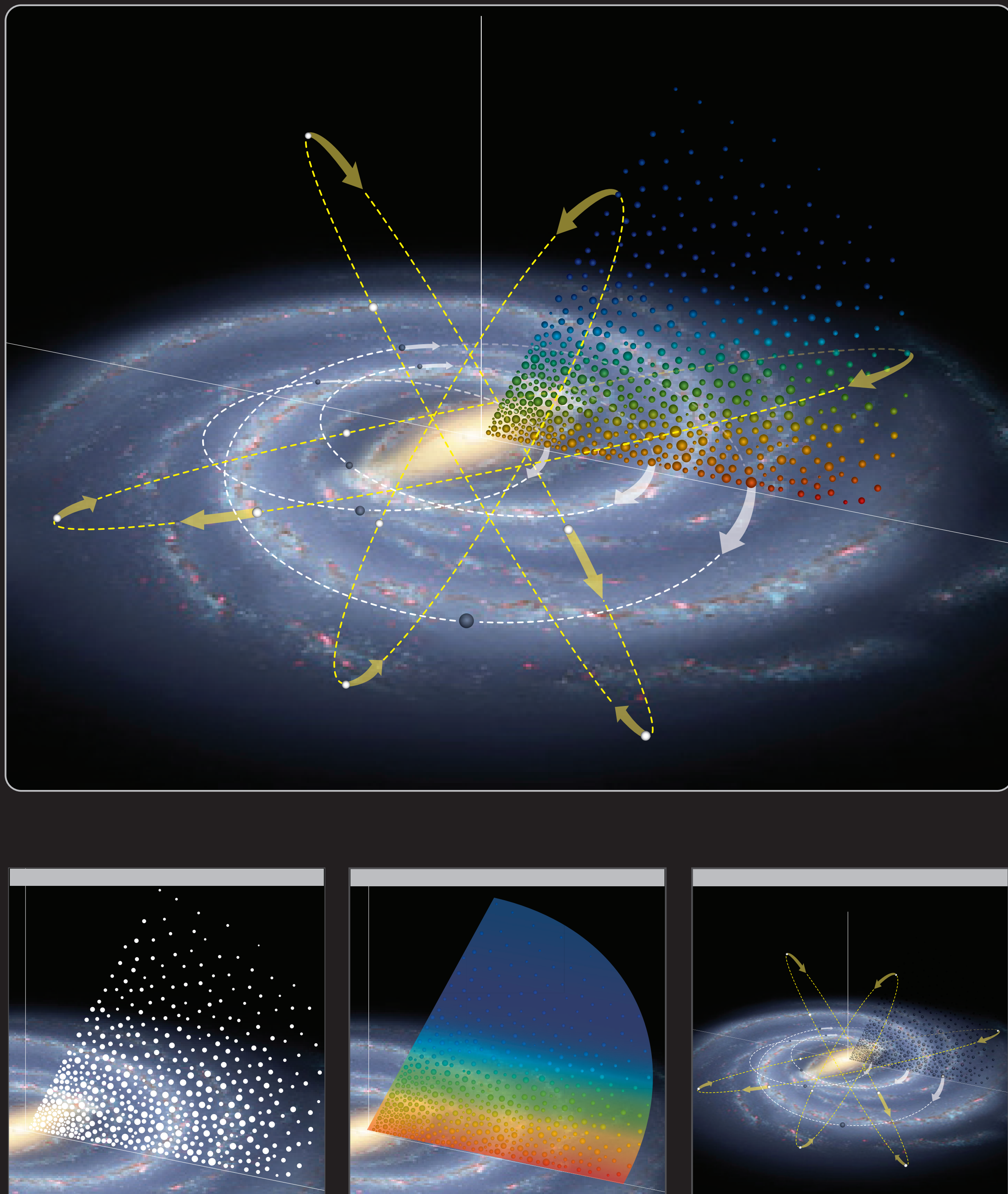
Lecture 14:

Open questions in galactic astronomy and modern sky surveys



1. **Number density**
2. **Metallicity**
3. **Kinematics**

These three distribution functions provide observational constraints for the model selection (models for galaxy formation and evolution)

How well do we know these distribution functions?

Two major goals for the Milky Way models

1. **The origin and evolution of thin and thick disks:** can we generate a model that simultaneously reproduces the spatial, kinematic and chemical distributions?

2. **The halo structure:** can we generate a model that simultaneously reproduces spatial and kinematic structure and substructure (including streams and dark matter)?

Examples of related observational questions:

- How do the properties of the bulge compare to those of the disk and the halo?

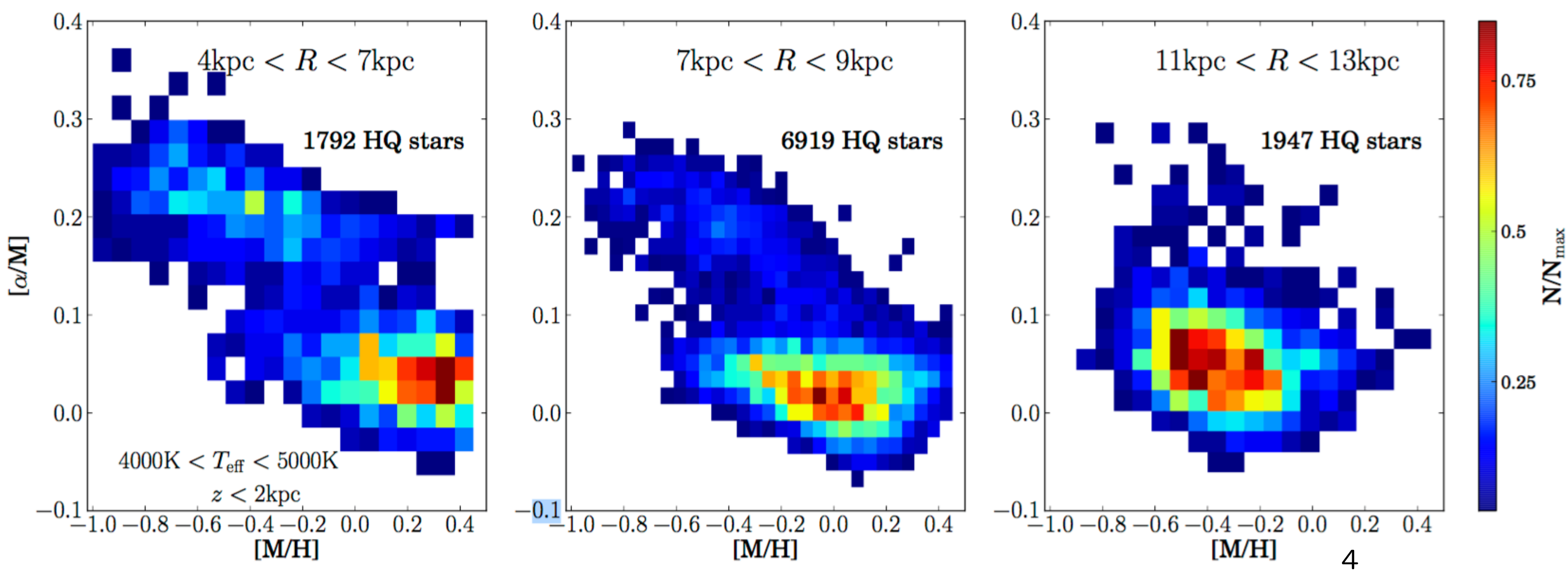
- What are the shapes of the density and velocity dispersion profiles of the stellar halo, and do they remain constant with increasing distance (and/or declining metallicity)?

- What fraction of halo is in substructures?

$[\alpha/Fe]$ vs. $[Fe/H]$ distribution for disk stars from SDSS APOGEE survey

- Anders et al. (2014, A&A 564, A115): strong variation of the $[\alpha/Fe]$ vs. $[Fe/H]$ distribution with the distance from the Galactic center

- Solar radius (8 kpc) is a transition zone between the "inner" and "outer" disks
- The inner disk is dominated by the thick disk and the metal-rich part of the thin disk
- The outer disk is dominated by the metal-poor part of the thin disk



$[\alpha/Fe]$ vs. $[Fe/H]$ distribution for disk stars from SDSS APOGEE survey

- Hayden et al. (2015, ApJ 808, 132): strong variation of the $[\alpha/Fe]$ vs. $[Fe/H]$ distribution with both R and Z!

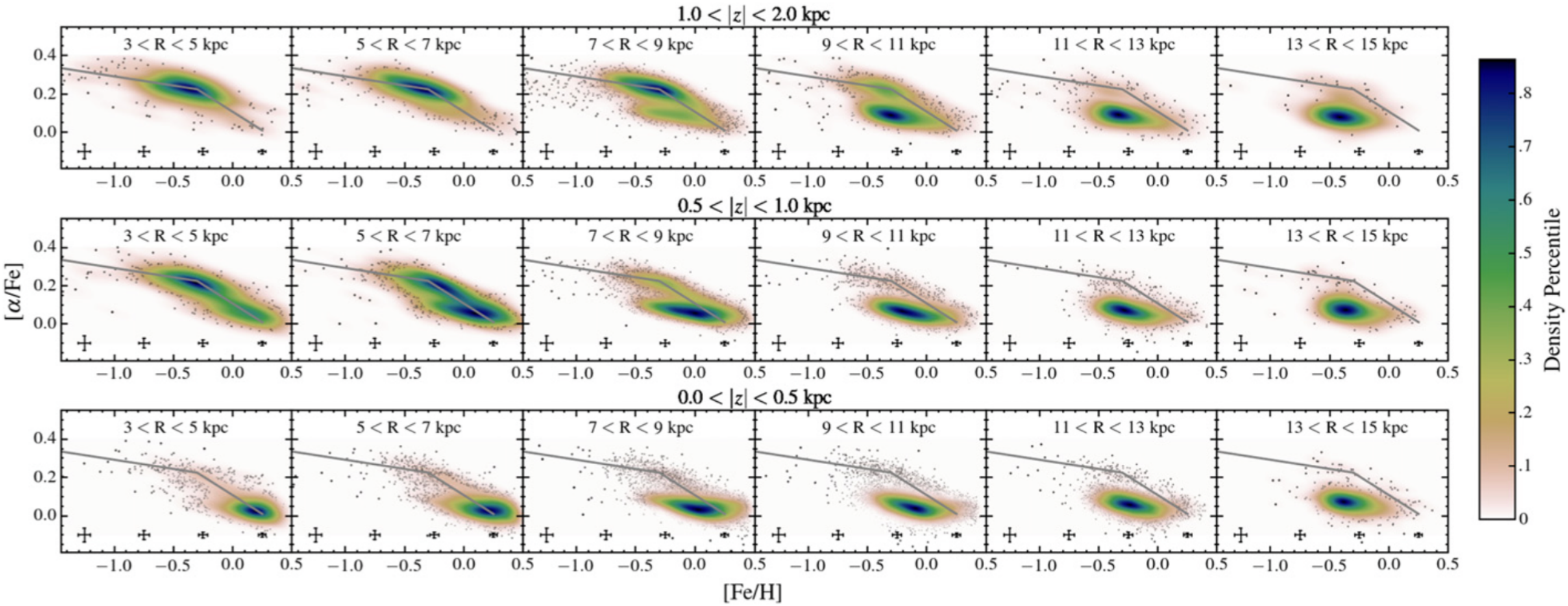
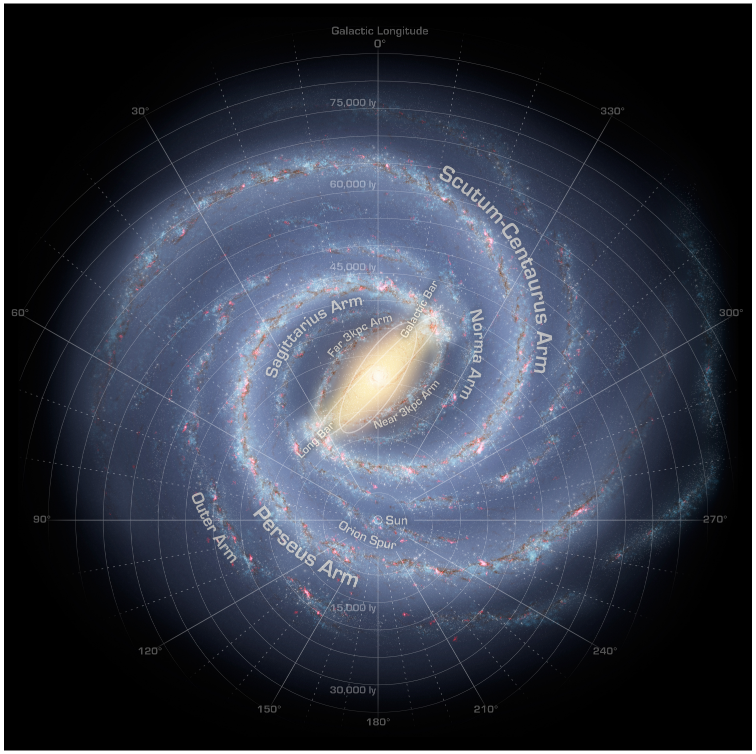
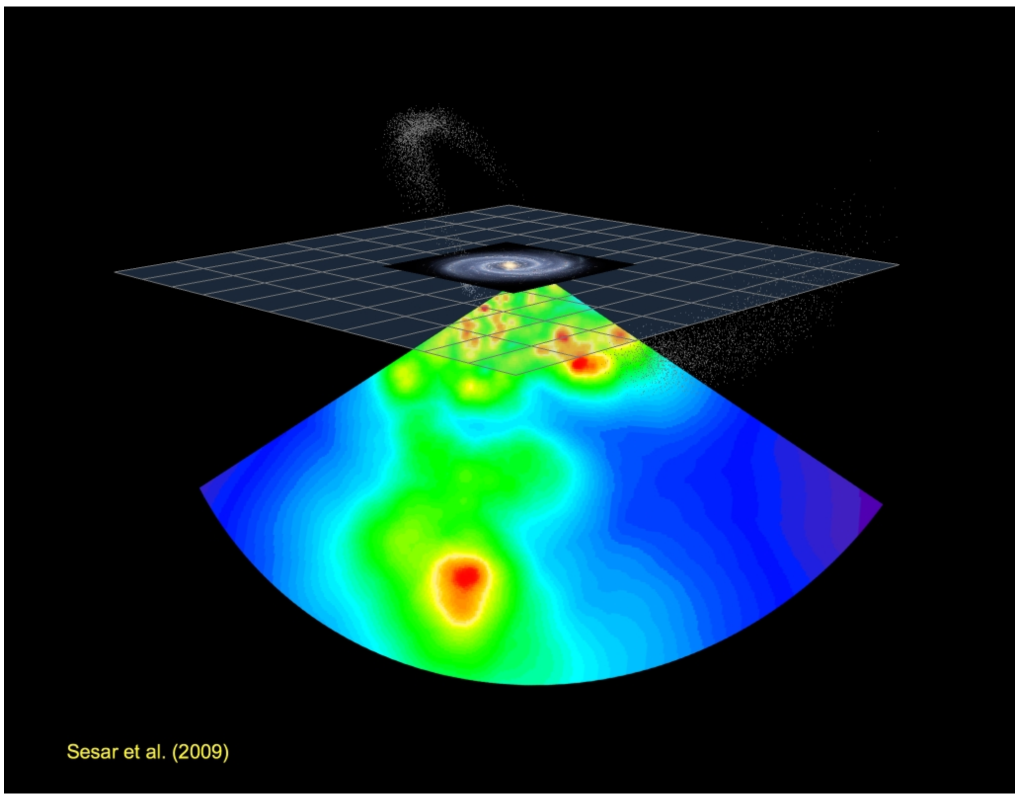


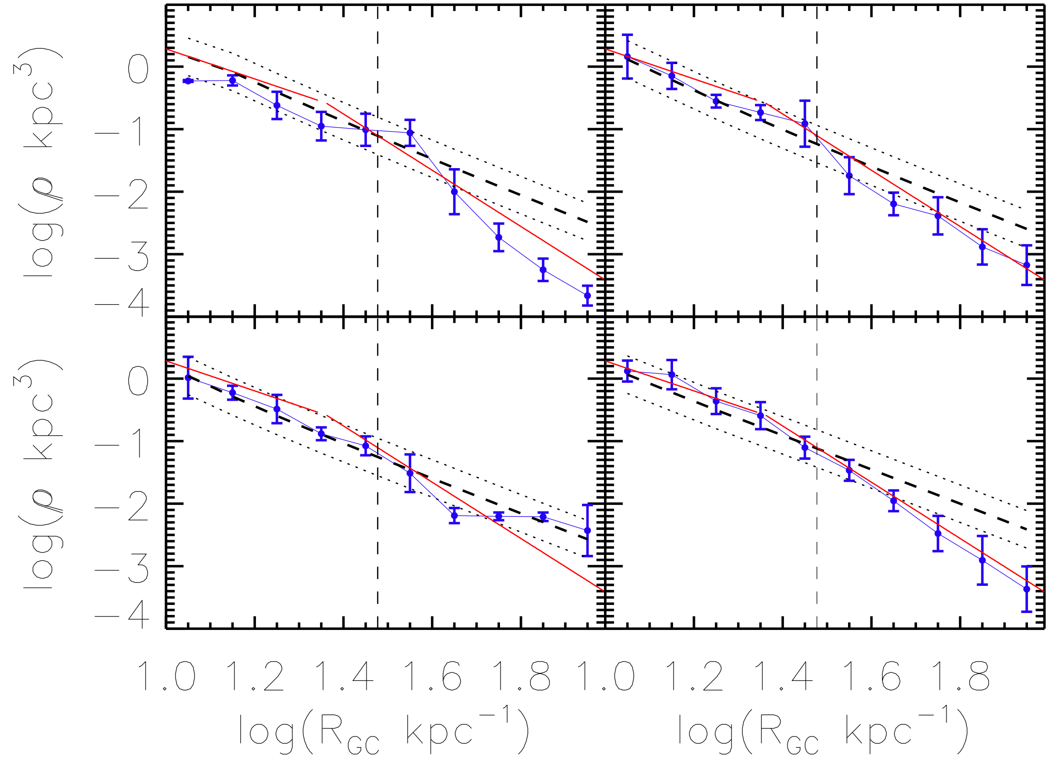
Figure 4. Stellar distribution of stars in the [α/Fe] vs. [Fe/H] plane as a function of R and $|z|$. The typical uncertainty in the abundances is shown as a function of metallicity across the bottom of each panel. The size of individual points is inversely related to the density at that location, to 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.

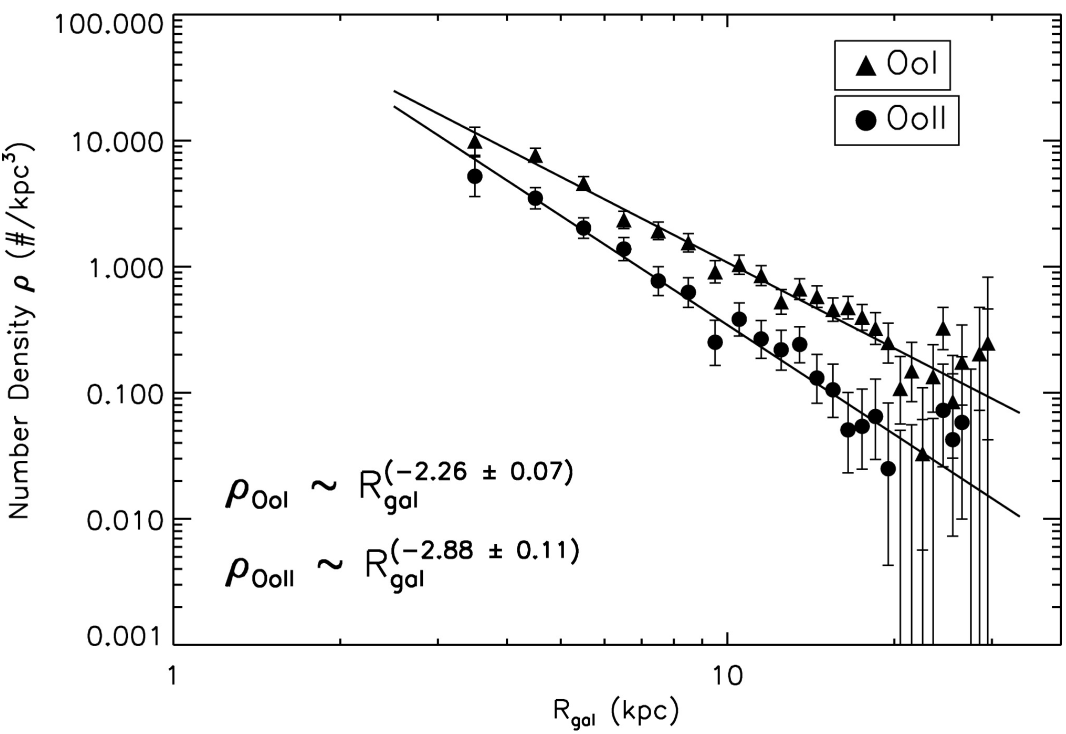




Outer halo studies: RR Lyrae from SDSS Stripe 82

- **Top left:** the disk structure (artist's conception based on the Spitzer and other surveys of the Galactic plane)
- **Bottom left:** the halo density (multiplied by R^3; yellow and red are overdensities relative to mean $\rho(R) \propto R^{-3}$ density) as traced by ~500 RR Lyrae from SDSS Stripe 82 (Watkins et al; Sesar et al. 2009), compared in scale to the top panel
- Conclusions: the spatial distribution of halo stars is highly inhomogeneous (clumpy); when averaged, the stellar volume density decreases as $\rho(R) \propto R^{-3}$.

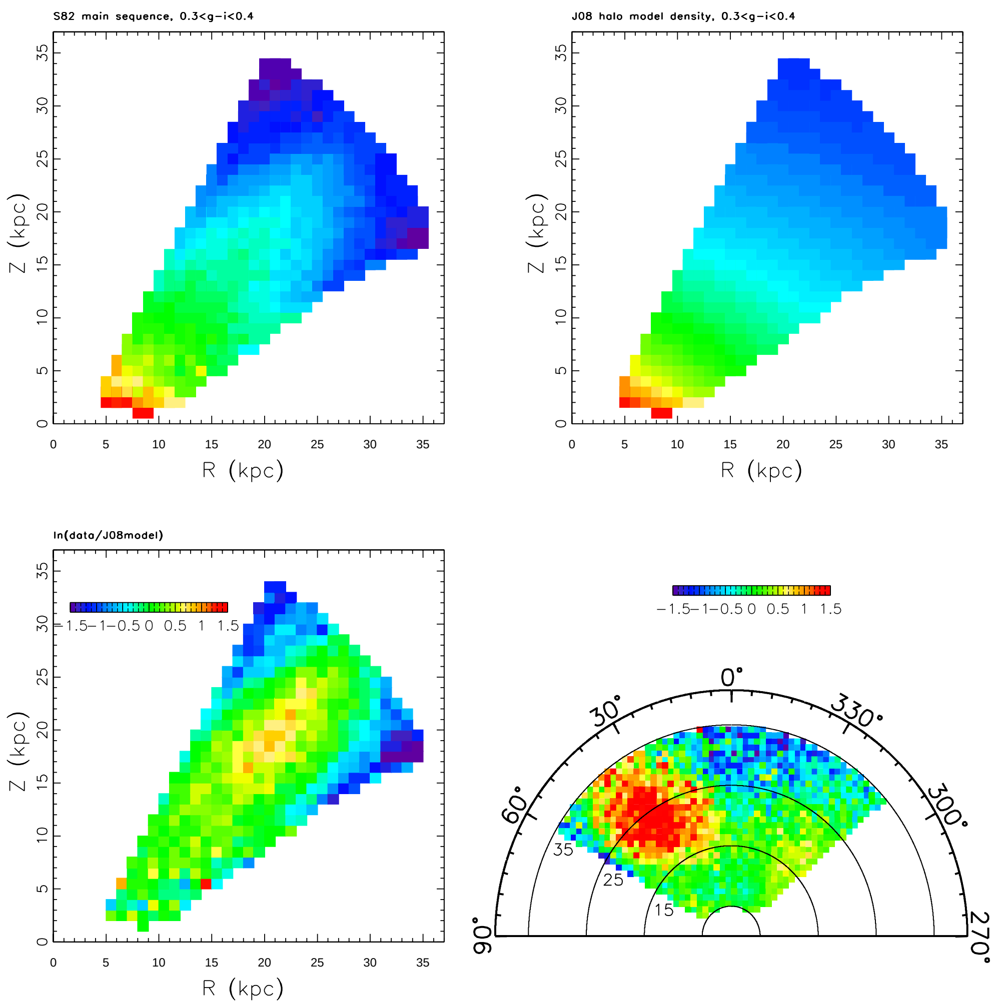




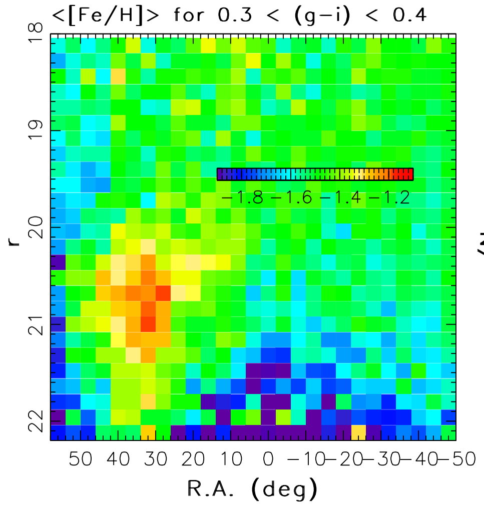
Outer halo studies: RR Lyrae from SDSS Stripe 82

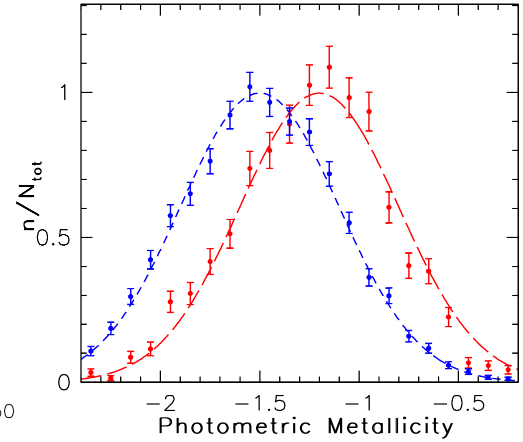
- **Top left panels:** four regions selected by R.A.; points: observed density, blue line: fit from Sesar et al. (2009); red lines: fit from Watkins et al. (2009); similar results for 2016 candidate RR Lyrae from SEKBO survey (Keller et al. 2008);
- **Bottom left panel:** Oosterhof I and II profiles for 838 LONEOS RR Lyrae from Miceli et al (2008); confirmed by stripe 82 RR Lyrae
- **Conclusions:** The density profile steepens beyond ∼30 kpc; within 30 kpc, the profile for Oosterhof II subset is steeper

Outer halo studies: main-sequence stars



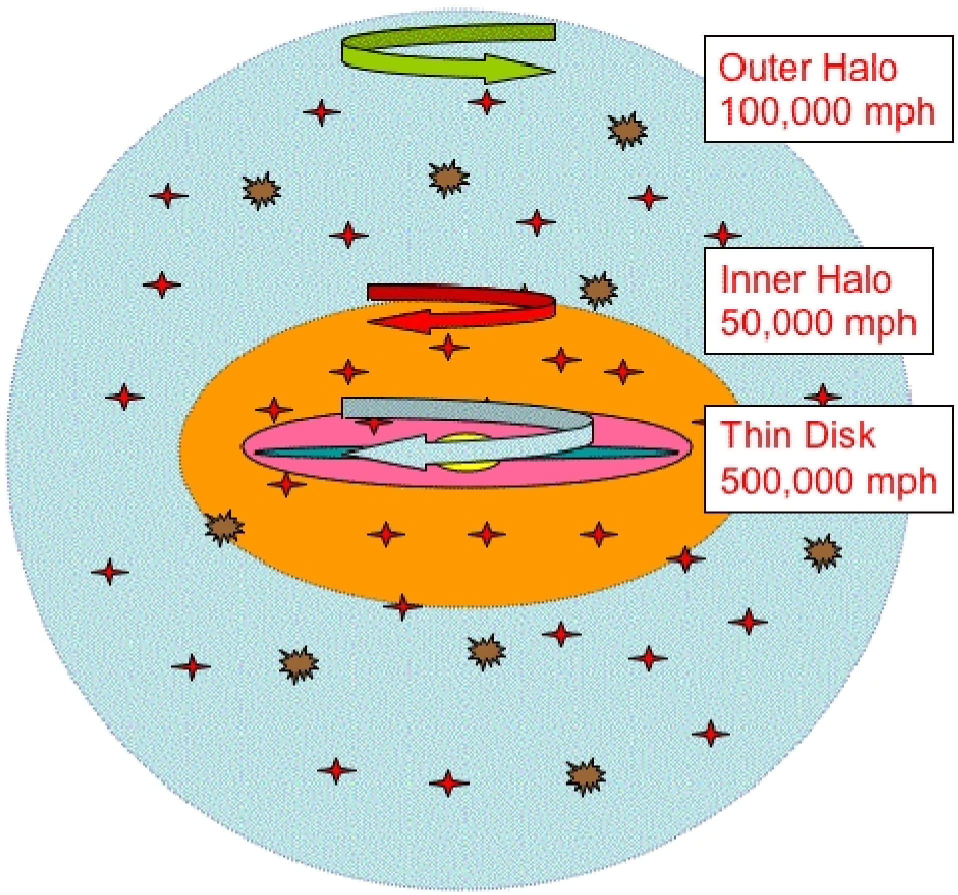
- Sesar et al. (2009): co-added SDSS Stripe 82 data enable mapping with numerous main-sequence stars out to ∼30 kpc
- **Top left:** Observed density map
- **Top right:** Galfast model prediction
- **Bottom left:** Data/model ratio, overdensity is the Sgr tidal stream
- **Bottom right:** Data/model ratio along the celestial equator
- Evidence for steepening of the density profile beyond ∼20 kpc from the Galactic center
- Consistent conclusion with the RR Lyrae spatial profile





Outer halo studies: main-sequence stars

- Evidence for steepening of the density profile beyond ∼20 kpc from the Galactic center
- Top left: evidence for drop in metallicity of smooth background halo beyond ∼20-30 kpc
- However, high surface-brightness overdensities have higher $[Fe/H]$, top right Supports simulation-based results by, e.g., Johnston et al. (2008) and Zolotov et al. (2009)
- Agrees with indirect results based on kinematics from Carollo et al. (2007) and Carollo et al. (2010), bottom panel



(Dark) Halo mass density profile

The Jeans equation for a steady-state rotationally invariant spherical system (see Lecture 7):

$$\frac{1}{\nu}\frac{d(\nu\sigma_r^2)}{dr} + \frac{2\beta\sigma_r^2}{r} \ = \ -\frac{d\Phi}{dr}$$

where $\beta = 1 - (\sigma_\theta/\sigma_r)^2$ (note that here "r" is the spherical galactocentric radius).

With $d\Phi/dr = GM(r)/r^2$, we can translate SDSS results to a constraint on $M(r)$. For example,

- Jurić et al. (2008) obtained for halo: $\nu(r) \propto r^{-2.8}$
- Bond et al. (2010) list $\sigma_r = 141$ km/s, $\sigma_\theta = 75$ km/s, and $\sigma_\phi = 85$ km/s

(Dark) Halo mass density profile: spherical case

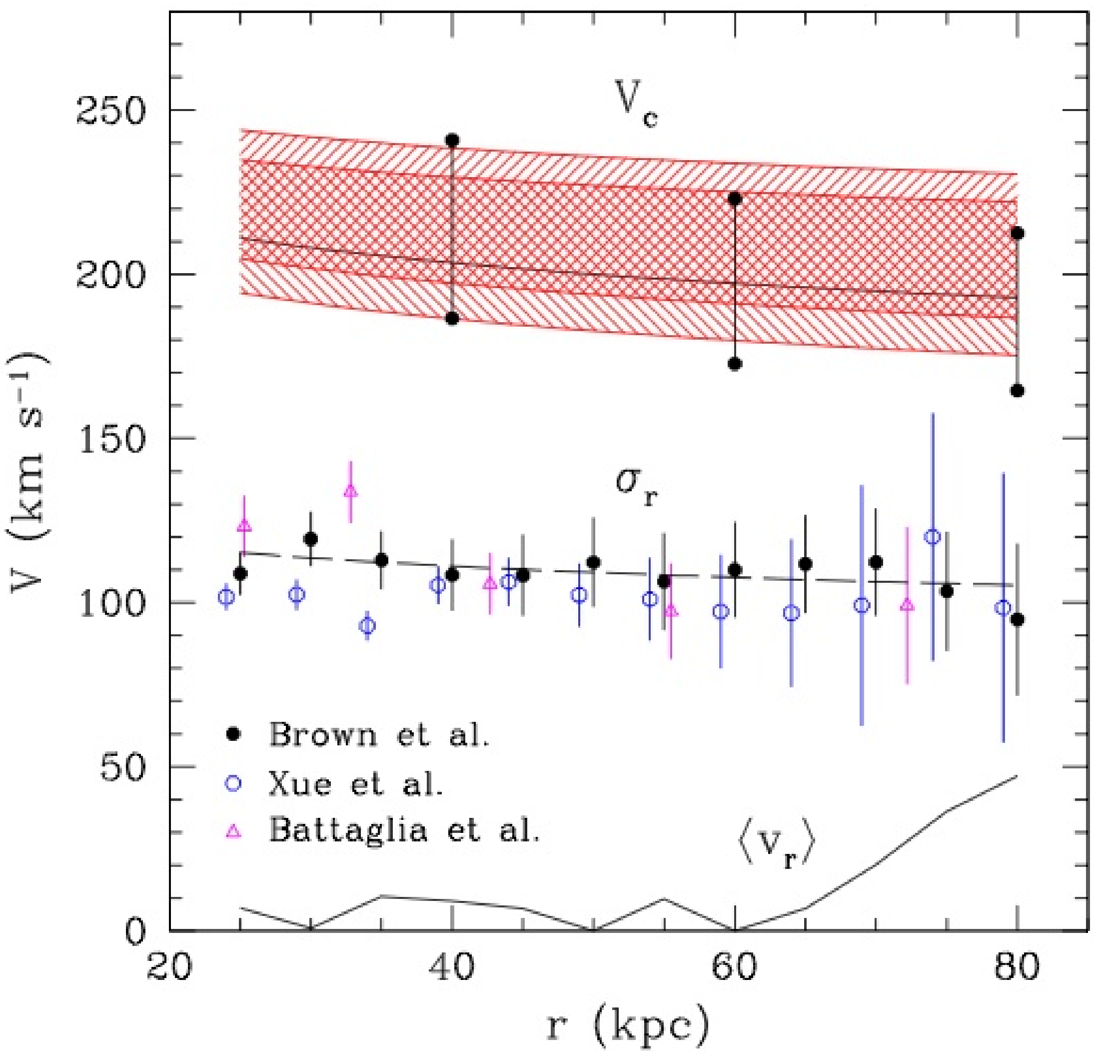
Ignoring for a moment that Jurić et al. (2008) obtained an oblate halo (c/a = 0.64), and that σ_θ and σ_ϕ are not equal (assume $\beta = 0.68$), it is easy to show that $M(r) \propto r$.

This $M(r)$ behavior implies a logarithmic gravitation potential $\Phi(r) = v_c^2\, ln(r/r_c)$, where v_c is the circular velocity, and r_c is a characteristic spatial scale.

More importantly, we also get $\rho(r) \propto r^{-2}$, where $\rho(r)$ includes **all** the matter!

This profile is the so-called "iso-thermal" profile and implies a flat rotation curve.

But what about the fact that we ignored departures from spherical symmetry for the halo density law? See Loebman et al. (2012, ApJ 758, L23) and Lecture 10.



Gnedin et al. (2010, ApJ 720, L108)

Halo radial velocity dispersion: profile at large radii

- Does the radial velocity dispersion vary in the outer halo?
- Data show only a little bit of gradient between $\sim$ 10 kpc and $\sim$100 kpc: Gnedin et al. (2010) get a power-law index of -0.08.
- If recent SDSS-based values from Bond et al. (2010) and Smith et al. (2009) are added, then the power-law index becomes -0.12.
- **We need better kinematic data in the 10-100 kpc distance range.**

Tentative Summary of Direct Halo Measurements

1. $\rho(R, Z, \phi)$:

   - Within ~10 kpc traced by main-sequence stars; oblate ($q = 0.64 \pm 0.1$), $\rho \sim 1/R^3$ ($n = 2.8 \pm 0.2$)

   - Within ~100 kpc traced by RR Lyrae stars; a steeper slope beyond 30 kpc and much more substructure, extends to at least ~100 kpc, within 30 kpc Oosterhof II subset have a steeper slope

2. $[Fe/H]$:

   - Within ~10 kpc traced by main-sequence stars; uniform gaussian distribution (gradient < 0.01 dex/kpc) centered on $[Fe/H] = -1.5$ with a dispersion of 0.3 dex

- Beyond ∼20-30 kpc, $[Fe/H]$ for the background diffuse population probably decreases; however, for high surface brightness substructure $[Fe/H] > -1.5$ (Sgr trailing tidal tail: $[Fe/H] = -1.2$, Monoceros stream: $[Fe/H] = -1.0$)

3. **Kinematics:**

- Within ∼10 kpc traced by main-sequence stars, no rotation to within 10-20 km/s, velocity ellipsoid aligned with the spherical coordinate system: $\sigma_R = 140$ km/s, $\sigma_\phi = 85$ km/s, $\sigma_\theta = 75$ km/s

- Limited data beyond 10 kpc; based on a heterogeneous sample of ∼250 objects, it appears that beyond ∼30 kpc the radial velocity dispersion is decreasing with R (to ~ 50 km/s at ∼120 kpc).

"We need mo' data!"