Astr 511: Galactic Astronomy

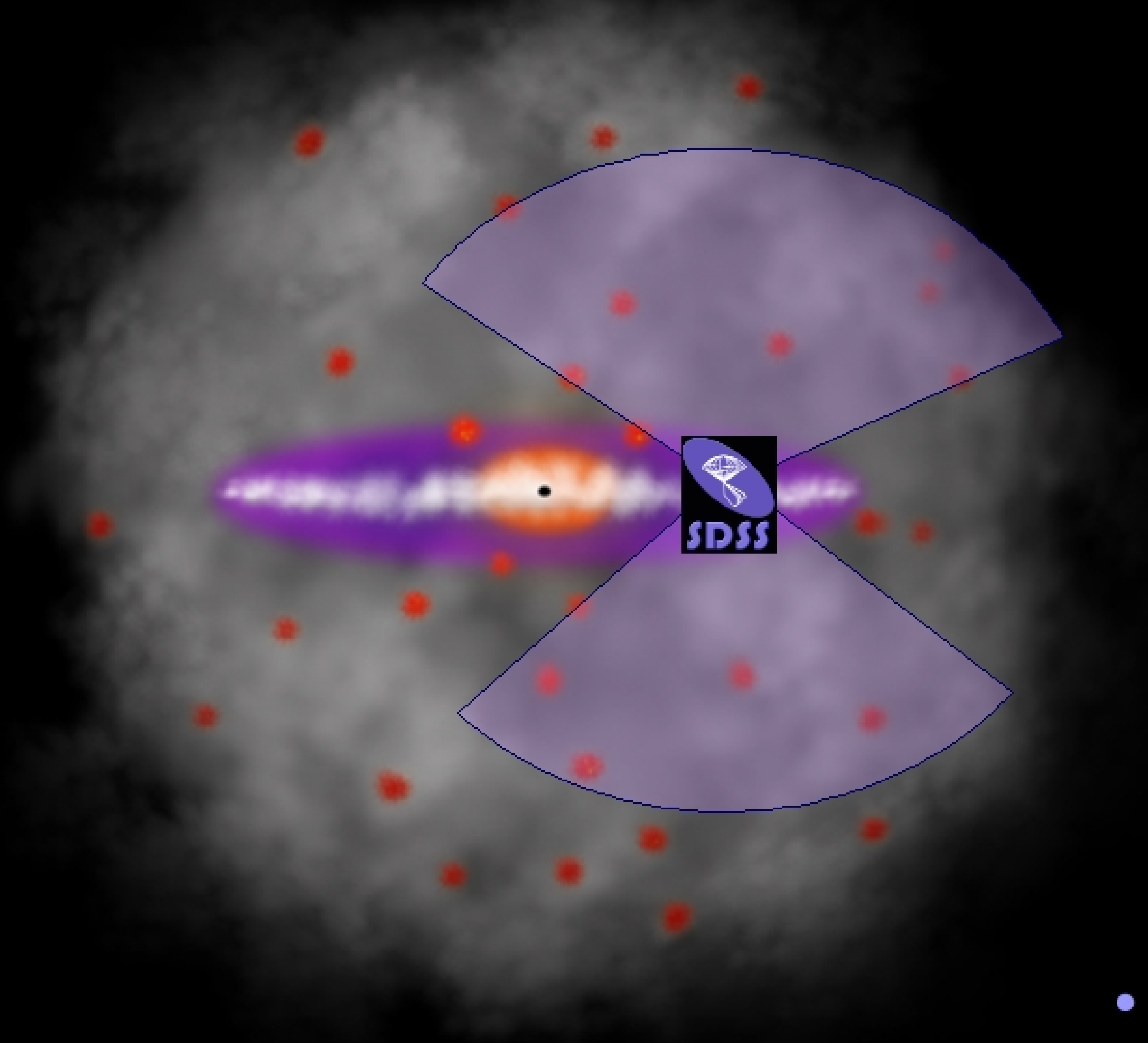
Winter Quarter 2015, University of Washington, Željko Ivezić

Lecture 6:

Stellar count distribution in the Milky Way

Please finish reading Ivezić, Beers & Jurić 2012 (ARA&A, 50, 251) within next two weeks!

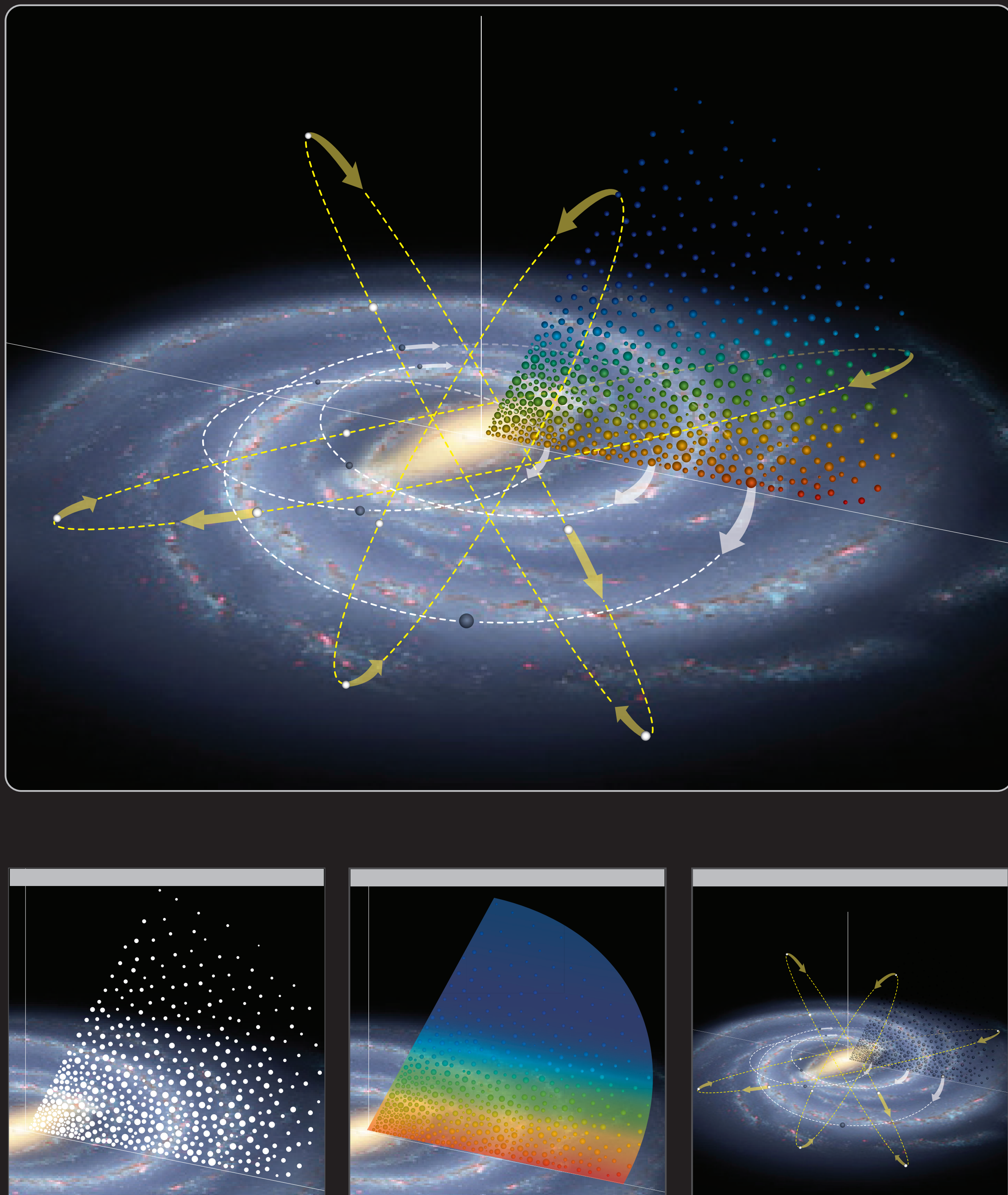
Classical Decomposition of the Milky Way Components



- Thin/thick disk
- Galactic bulge
- Stellar halo

- Components trace the DM dominated potential

- They are a product of Milky Way formation and evolution



The three basic stellar distribution functions:

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

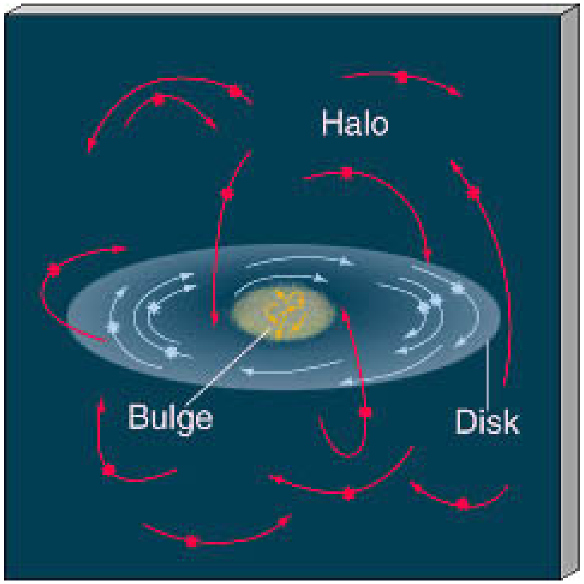
These three distribution functions provide observational constraints for the model selection (models for galaxy formation and evolution)

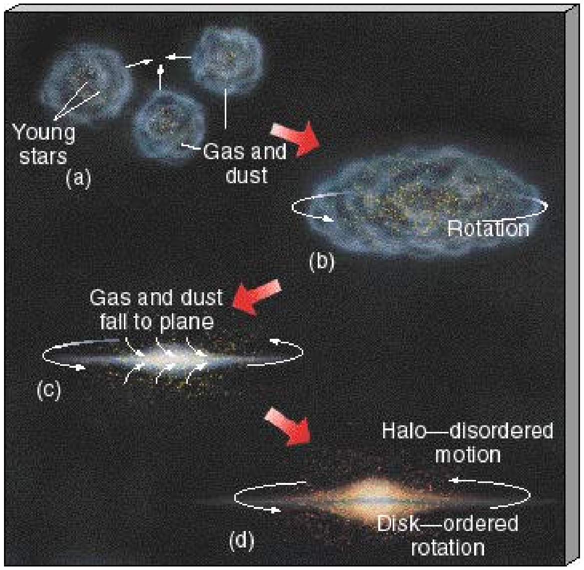
Galaxy Formation Scenarios (abridged)

The ELS Monolithic Collapse Model

- The ELS model (Eggen, Lynden-Bell and Sandage, 1962): the Milky Way formed from the rapid collapse of a large proto-galactic nebula: top-down scenario

- Searle & Zinn (1978): galaxies are built up from merging smaller fragments: a bottom-up scenario





Problems with the ELS collapse scenario:

- Why are half the halo stars in retrograde orbits? We would expect that most stars would be moving in roughly the same direction (on highly elliptical orbits) because of the initial rotation of the proto-Galactic cloud.

- Why there is an age spread of $\sim$ 3 Gyr among globular clusters (GCs)? We would expect $<$ 1 Gyr spread (free-fall time).

Some important questions that are left without robust answers:

- Why GCs become more metal-poor with the distance from the center?

- Detailed calculations of chemical enrichment predict about 10 times too many metal-poor stars in the solar neighborhood (the G-dwarf problem), why?

Which model for galaxy formation is correct (or less wrong)?

- by observing galaxies at large redshifts (beyond 1), we are probing the epoch of galaxy formation – indeed, galaxies at large redshifts have very different morphologies, and the fraction of spirals in clusters is greater than today (Butcher-Oemler effect). Also, the volume density of galaxies was larger in the past: appears consistent with the bottom-up approach

- We have some important detailed evidence for galaxy merging in our own backyard: the Milky Way structure and kinematics

- How smooth, or clumpy, is the distribution of stars and their kinematics in the Milky Way?

The Milky Way Structure, as seen by SDSS

1. Spatial Distribution of Stars

2. Metallicity Distribution

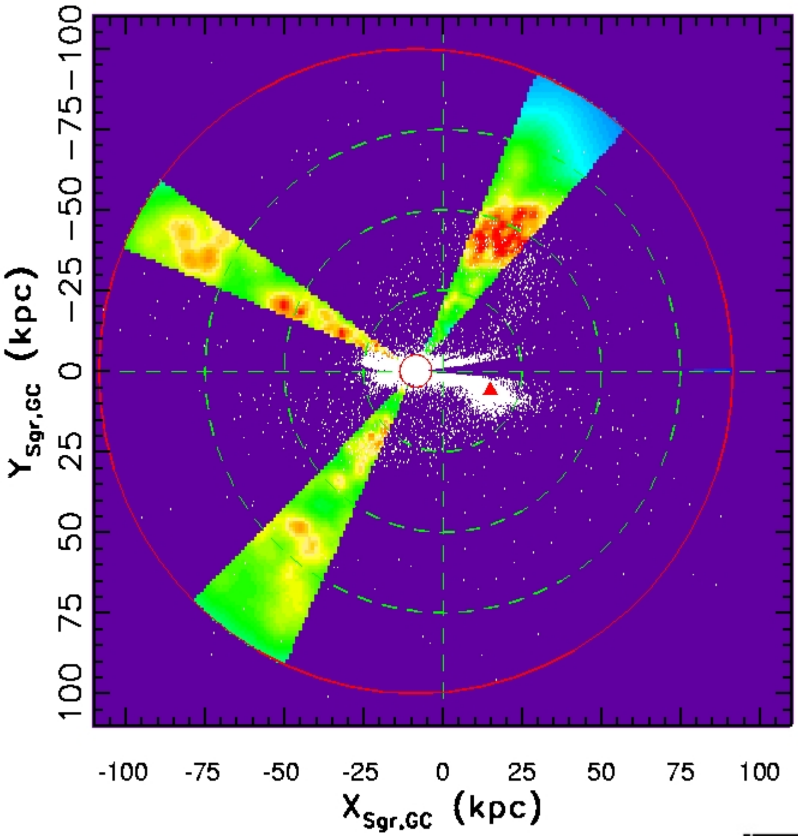
3. Stellar Kinematics

Advantages of SDSS for studying the Milky Way structure

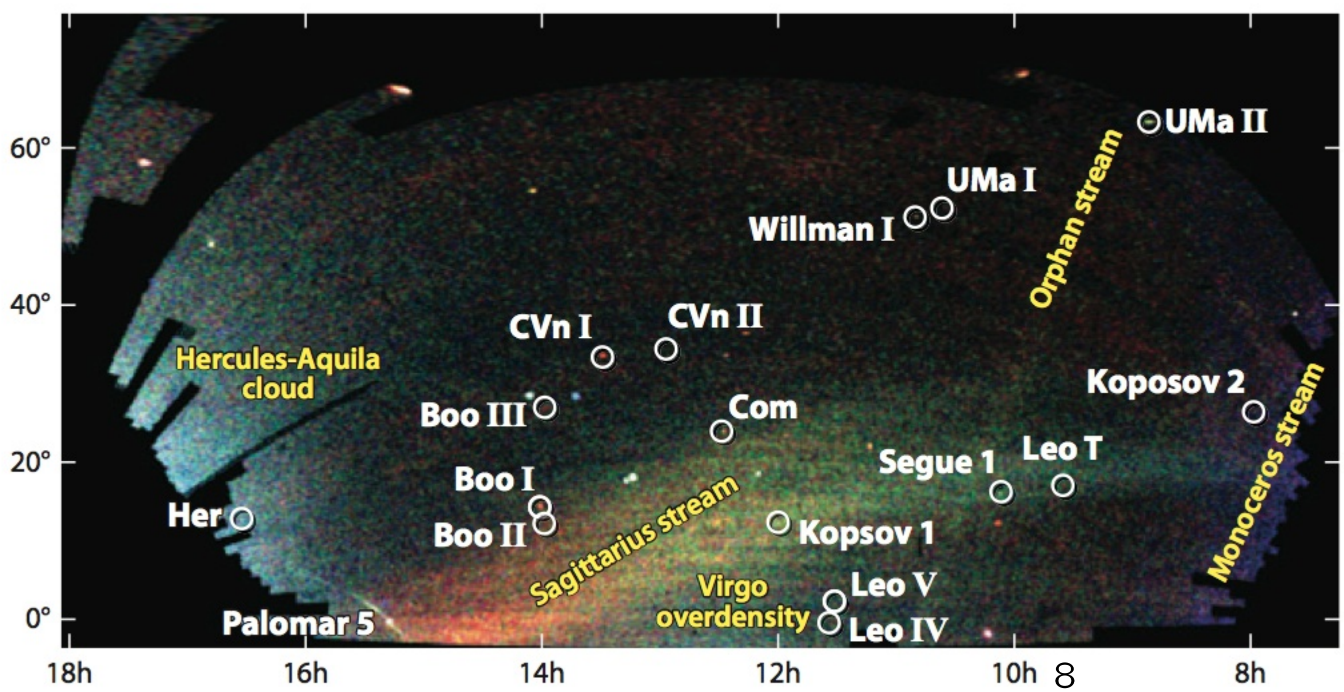
- Accurate photometry: distance and [Fe/H] estimates

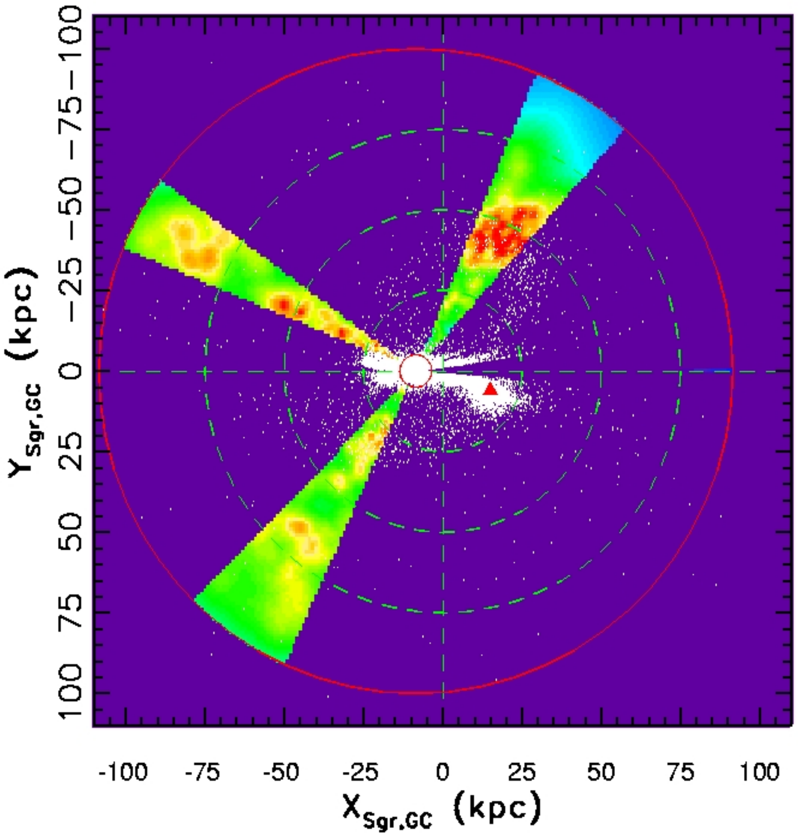
- Numerous stars: small random errors for number density

- Large area and faint limit: good volume coverage



- SDSS RR Lyrae and other luminous tracers, and 2MASS M giants, demonstrate that the Milky Way halo extends to ∼100 kpc and has a lot of substructure
- The color-coded map of RR Lyrae density (times R^3) uses a Bayesian density estimator from Ivezić et al. (2005).
- The map below is from Belokurov et al. (2007) (∼10 kpc scales)





$$n_o = \frac{C}{\sum_{i=1}^{N} d_i^D}$$

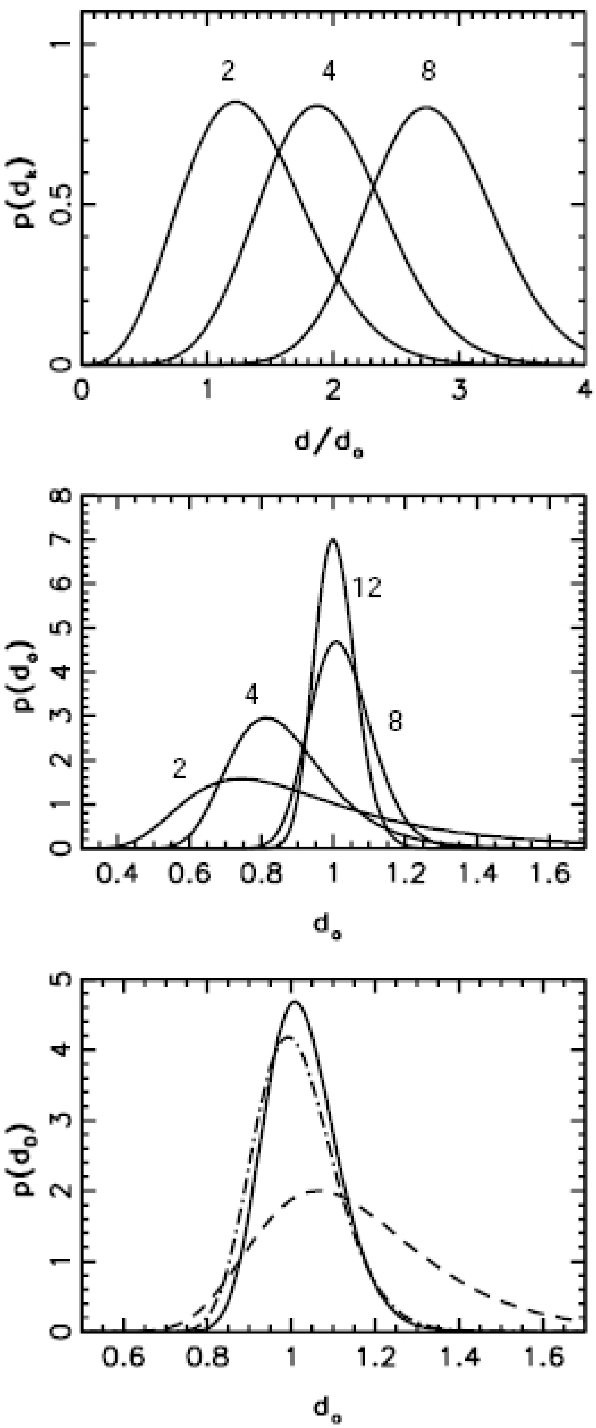
where C can be estimated by requiring $< n_o >= N_{tot}/V_{tot}$.

Density traced by a point distribution

- Given N points distributed in D-dimensional space, the volume number density, n_o, can estimated using the distance to the Nth nearest neighbor as

$$n_o = \frac{N}{V_D(d_N)},$$

  where $V_D(d)$ is evaluated according to the problem dimensionality, D (for $D = 3$, $V_3(d) = 4\pi d^3/3$, and $V_2 = \pi d^2$ for $D = 2$).
- More generally, distances to *all* N nearest neighbors contain information about the local density, and this information can be easily incorporated into a density estimator within the Bayesian probability framework. Following Ivezić et al. (2005, AJ 129, 1096; see Appendix B), see left.
- More density estimation methods can be found in astroML!



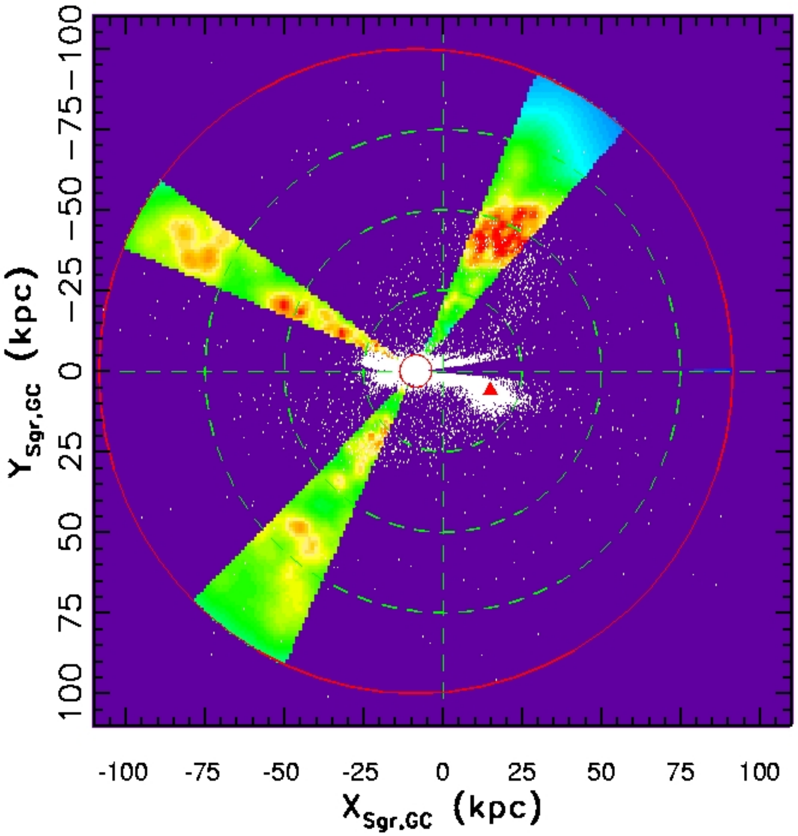
Density traced by a point distribution

- n_o is the *mean* density, however, the method gives the full posterior probability distribution for the local density

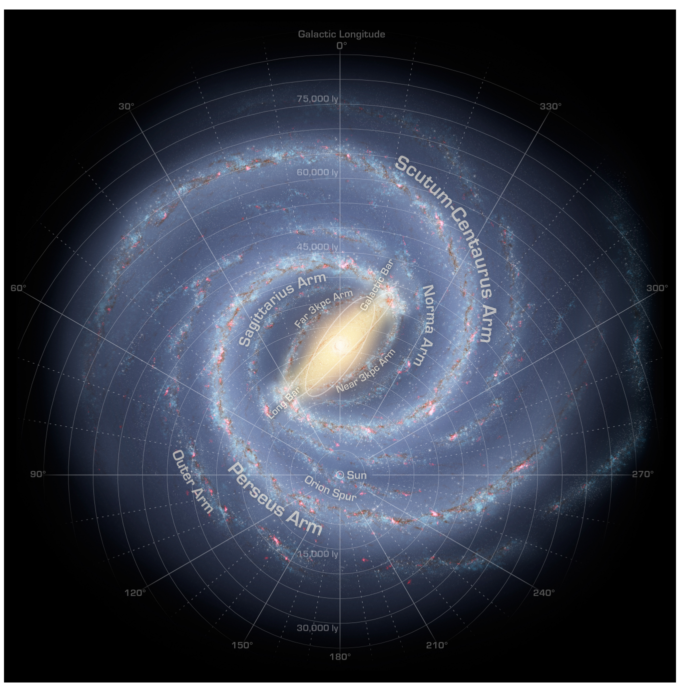
$$p(d_o|\{d_k; k=1,N\}) \propto \prod_{k=1}^{N} \frac{2e^{-(d_k/d_o)^2}}{d_o\,(k-1)!} \left(\frac{d_k}{d_o}\right)^{2k-1}$$

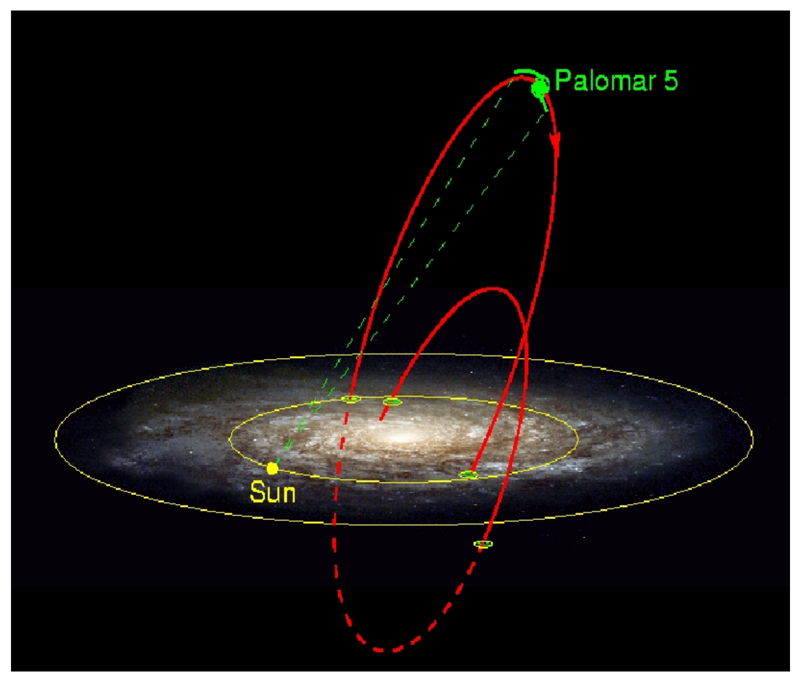
where $n_o = \pi\, d_o^2$.

- **Left:** The **top** shows the $k^{\rm th}$ nearest neighbor (NN) distance distribution, k=2, 4 and 8, for a random 2-dim. sample. The **middle** panel displays the evolution of the posterior probability density distribution, $p(d_o|...)$, for a sample with true $d_o = 1$. The dashed line in the **bottom** panel shows a typical $p(d_o|...)$ based on only the 8th NN in a random sample with $d_o = 1$. The dot-dashed curve shows $p(d_o|...)$ based on all 7 nearest neighbors. This distribution is used as the prior to evaluate the final $p(d_o|...)$ based on all 8 NN (solid line).



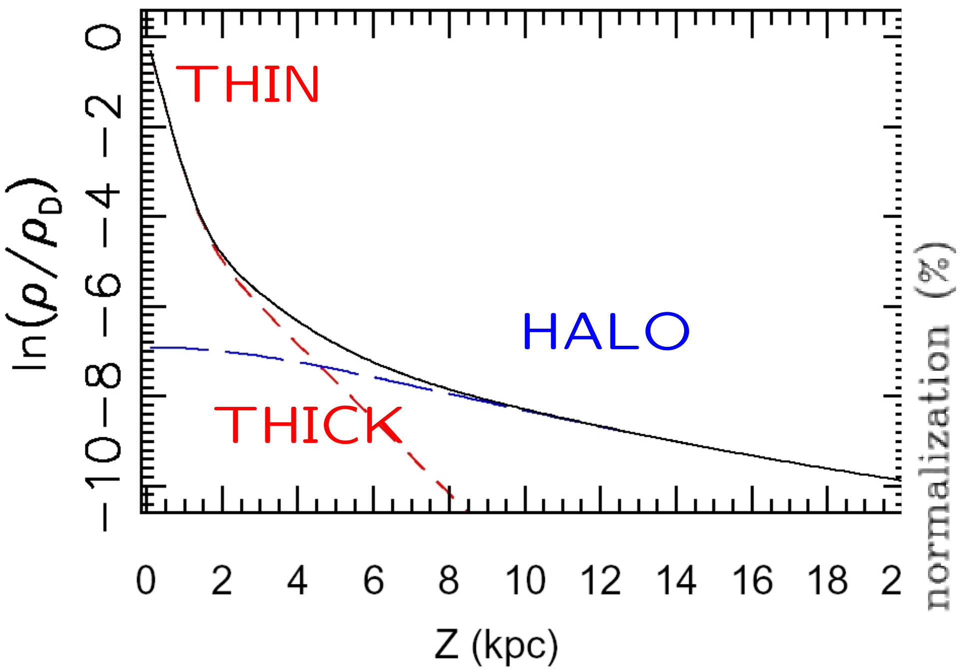
- SDSS RR Lyrae and other luminous tracers, and 2MASS M giants, demonstrate that the Milky Way halo extends to ∼100 kpc and has a lot of substructure
- SDSS has obtained excellent photometric data for over 100 million stars. How can one utilize these data for studying the disk component?
- What is the structure of the disk component, including kinematics and metallicity distributions?

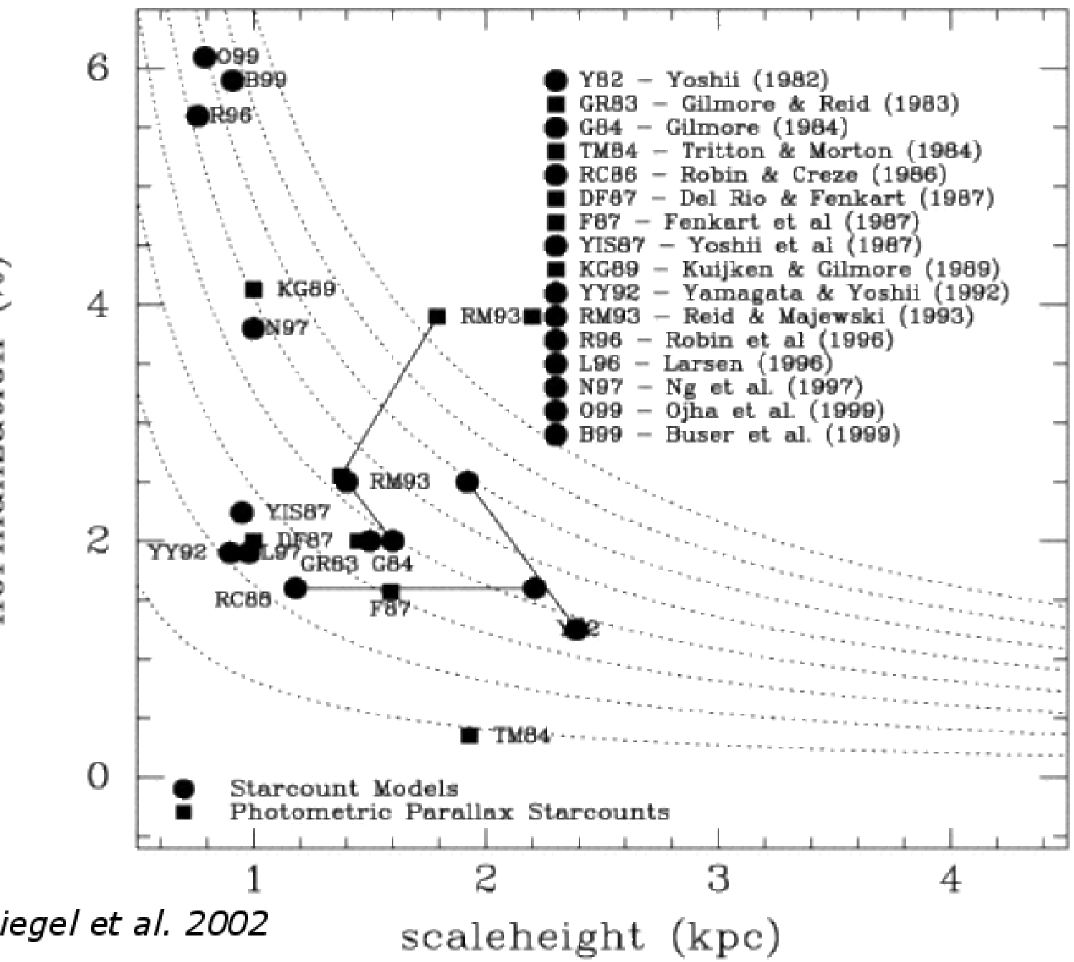




Constraining Thin/Thick Disk+Halo Models

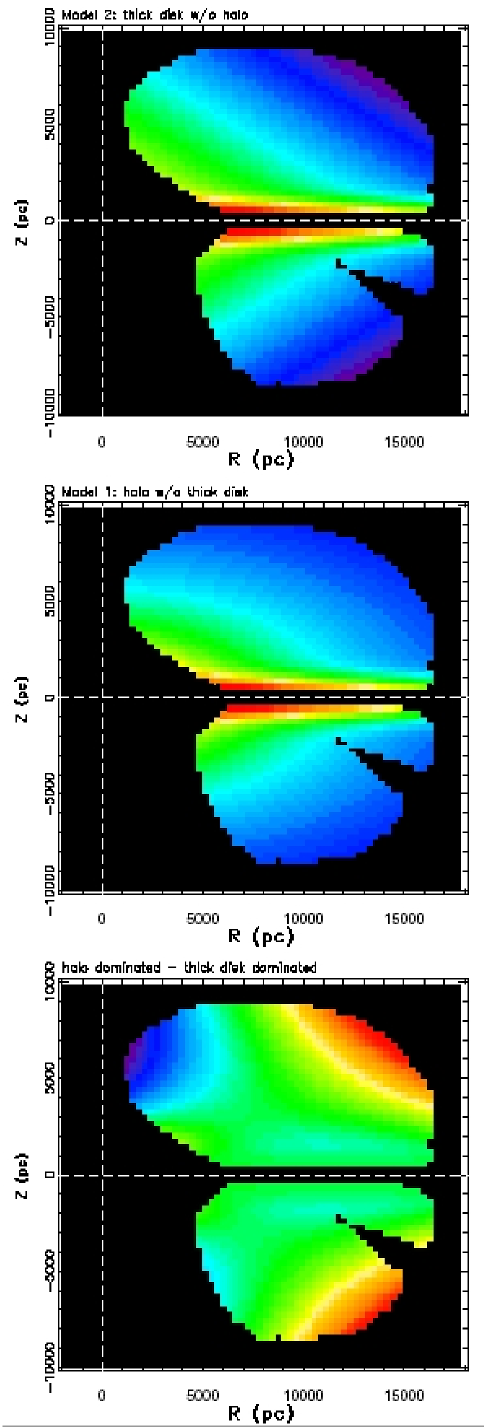
- Observationally, $\rho(z|R = R_\odot)$ is well fit by a sum of double exponential (thin and thick disk) and power-law profiles.
- However, **the best-fit models are degenerate:** e.g. the thick disk scale height varies by a factor of few and its normalization by an order of magnitude!



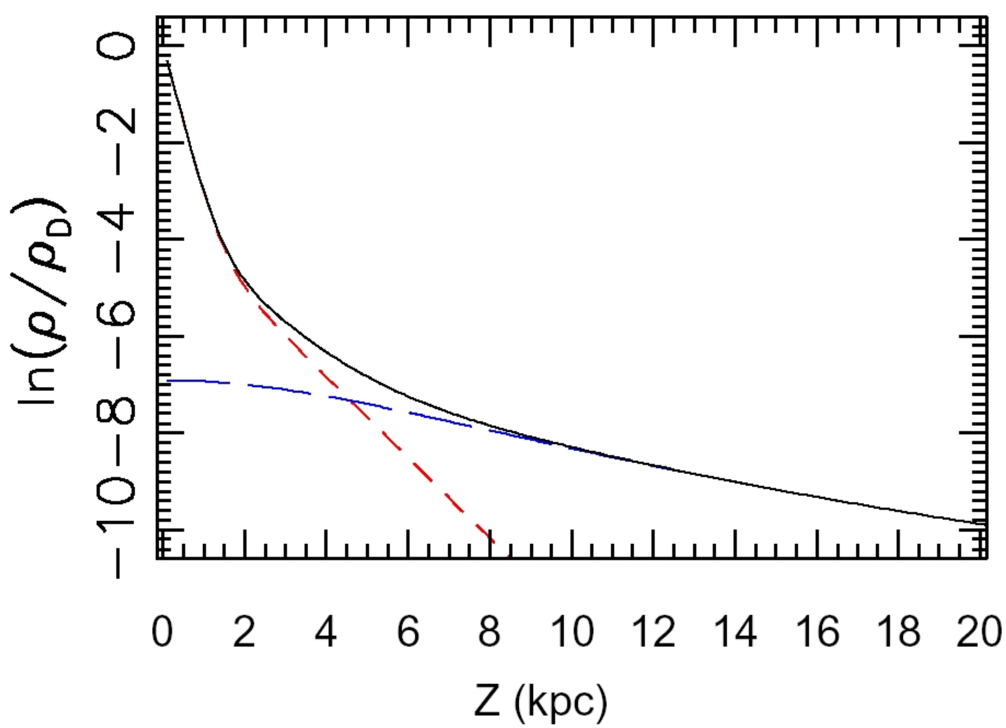


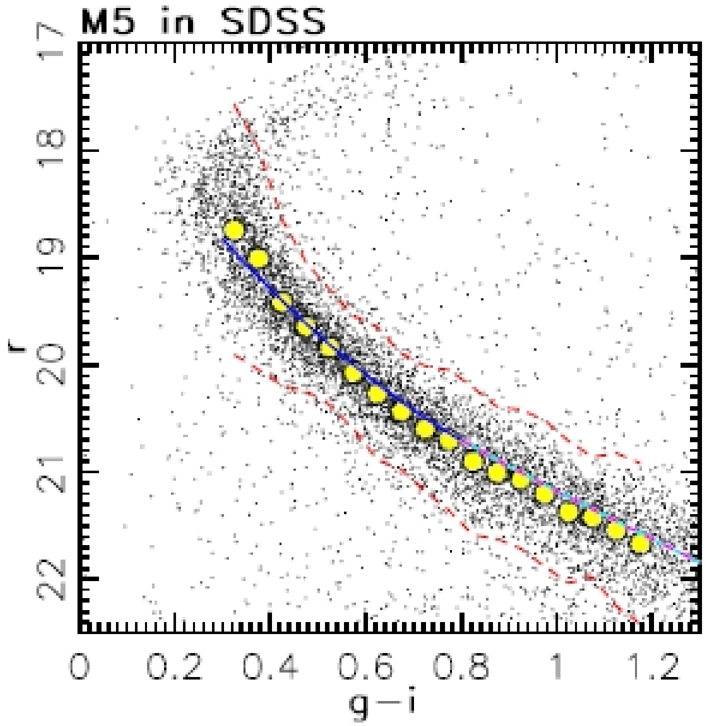
Siegel et al. 2002

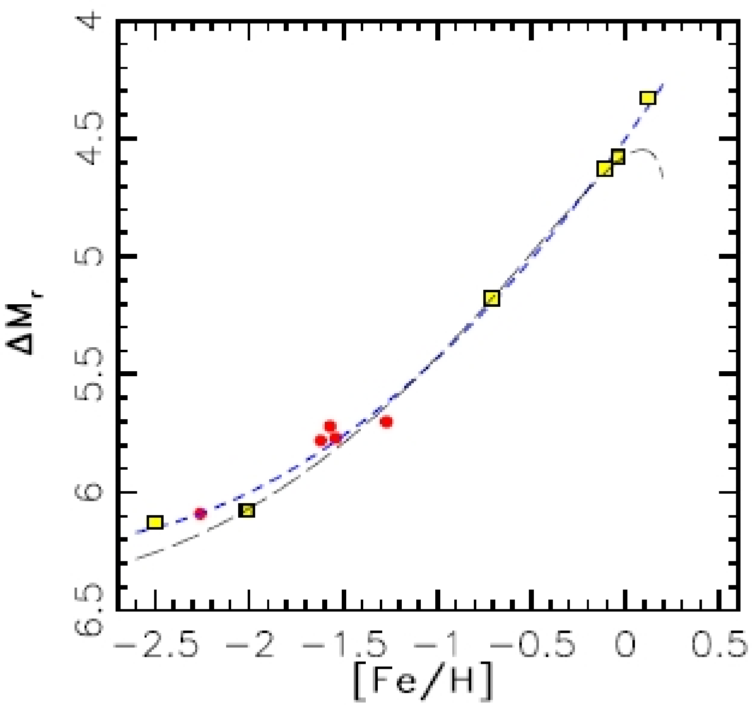
Constraining Thin/Thick Disk+Halo Models



- Observationally, $\rho(z|R=R_\odot)$ is well fit by a sum of double exponential (thin and thick disk) and power-law profiles.
- But, very different models (top: thin and thick disk without halo; middle: single disk and halo, bottom: the difference) can produce the same $\rho(z|R=R_\odot)$
- A large sky area is needed to break model degeneracies (pencil beam surveys are inconclusive)
- SDSS is the first survey with the required data

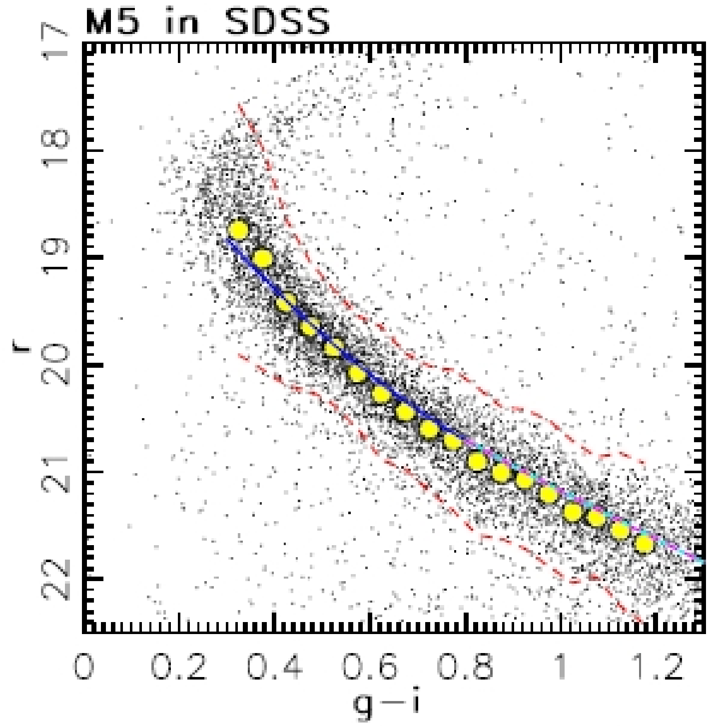


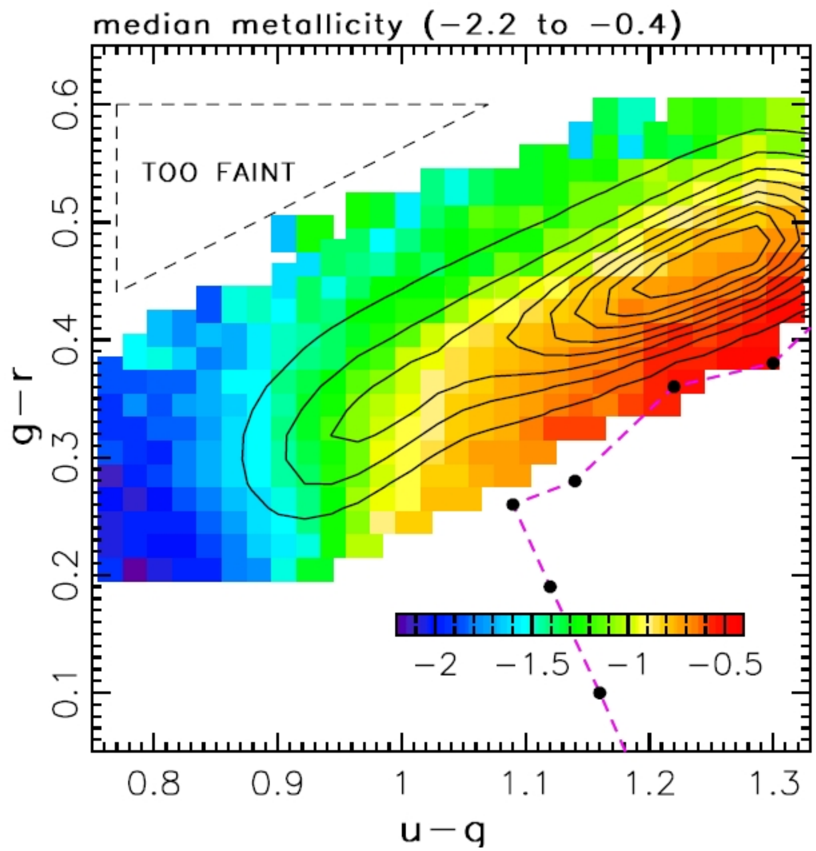




Photometric Distance and Photometric [Fe/H]: reminder

- Determined absolute magnitude vs. color vs. metallicity relation using globular clusters observed by SDSS (blue end), and nearby stars with trigonometric parallaxes (red end)
- The $g - i$ color of a main-sequence star constrains its absolute magnitude to within 0.1-0.2 mag (0.3 mag for unresolved binaries), assuming [Fe/H] is known





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- For F and G stars ($0.2 < g-r < 0.6$), accurate SDSS $u-g$ color measurements enable photometric metallicity estimates as precise (0.1-0.2 dex) as [Fe/H] derived from SDSS spectra

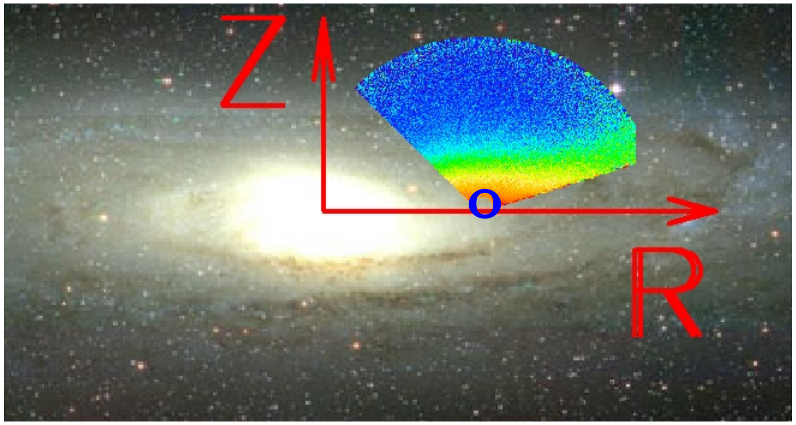
Dissecting Milky Way with SDSS

Good ugriz photometry gives decent distance (and metallicity) estimates for PRACTICALLY EVERY SINGLE STAR within areal and flux (and color) limits, and greatly simplifies the data analysis:

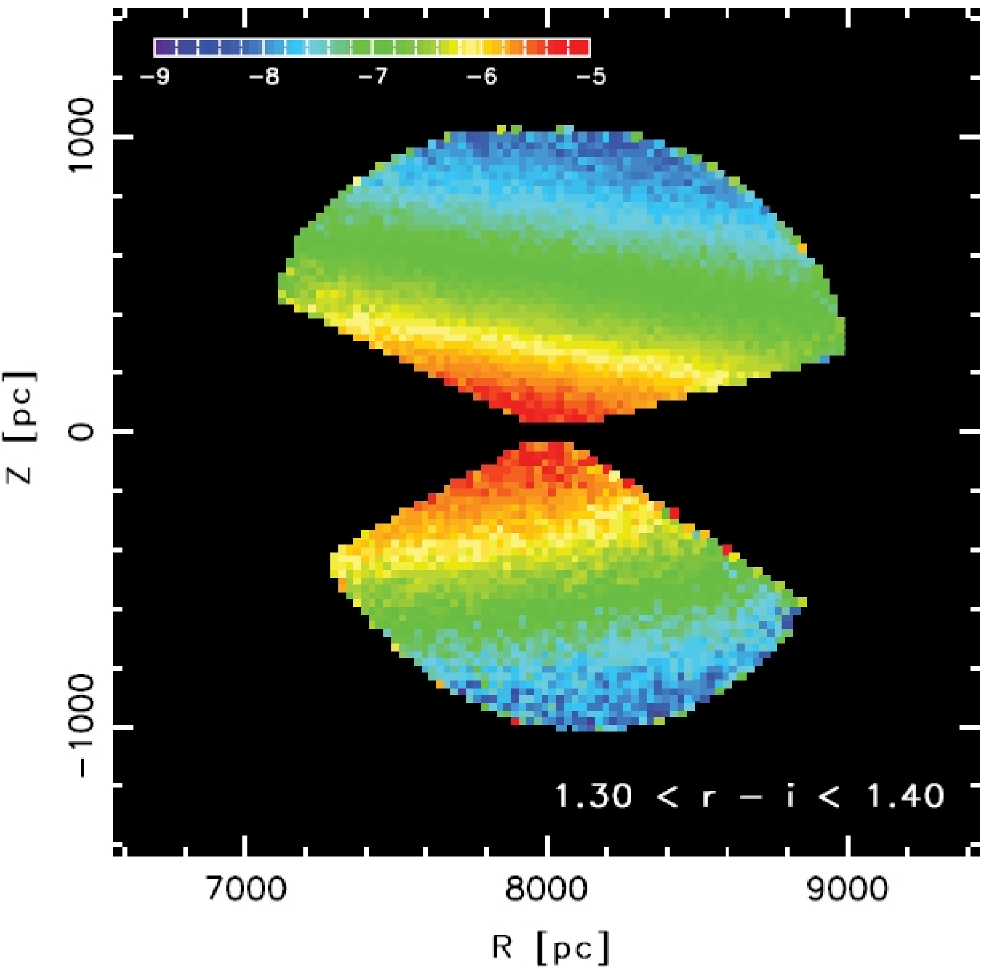
- Traditional approach: assume initial mass function, fold with models for stellar evolution; assume mass-luminosity relation; assume some parametrization for the number density distribution; vary (numerous) free parameters until the observed and model counts agree. Uniqueness? Validity of all assumptions?

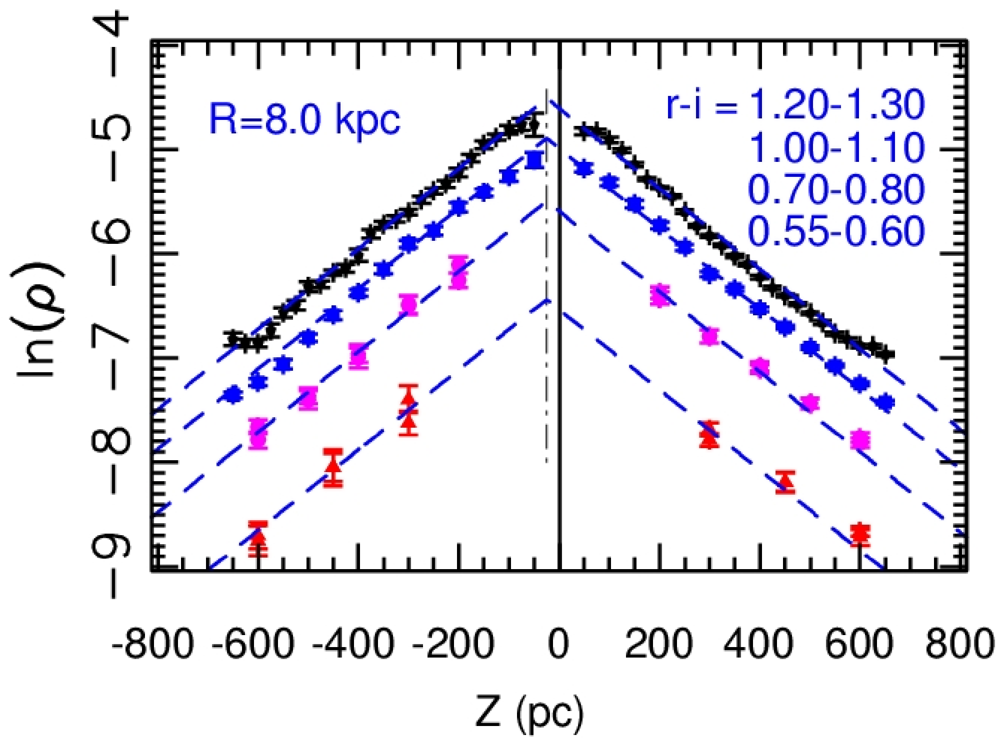
- SDSS photometric parallax approach: adopt color-luminosity relation, estimate distance to each star, bin the stars in XYZ space and directly compute the stellar number density (for each narrow color bin). There is no need to a priori assume, the number of, and analytic form for Galactic components

Local maps: thin disk



- Red(ish) stars have small luminosity: sampled to a few kpc
- Out to ∼1 kpc, the maps are roughly consistent with an exponential disk: the lines of constant density are straight lines
- The slope of these lines is given by the ratio of exponential scale height and scale length

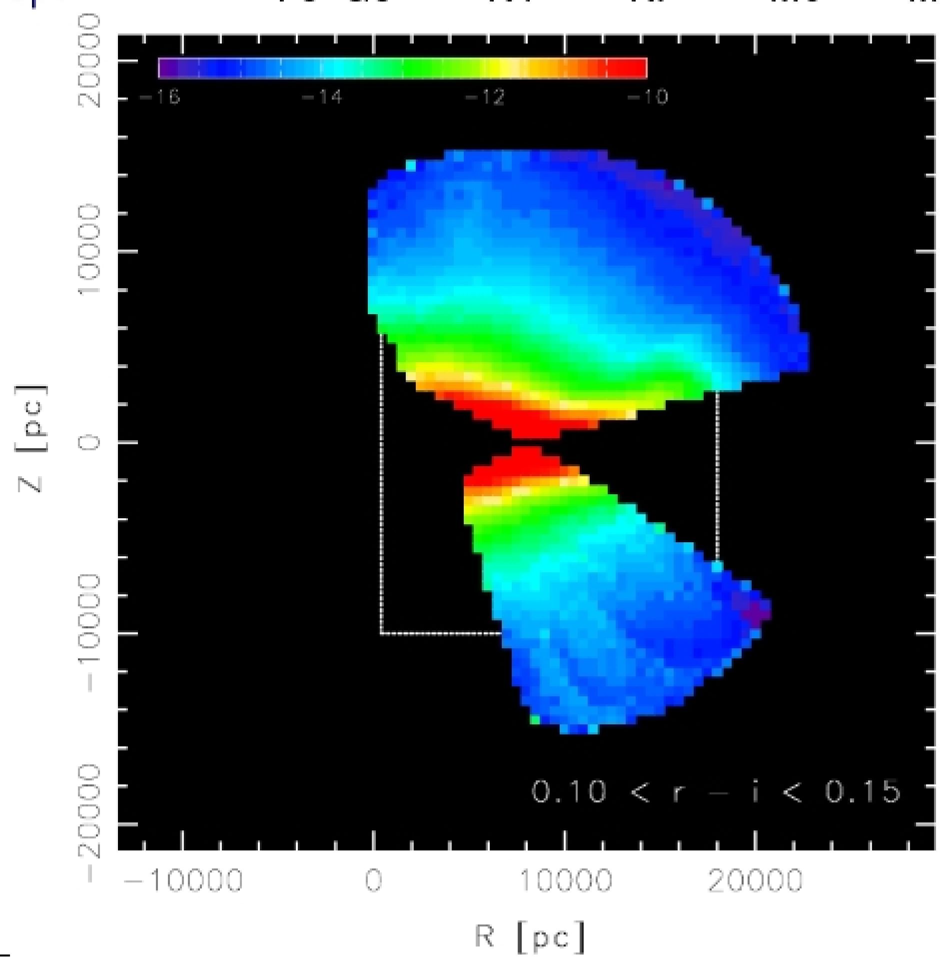


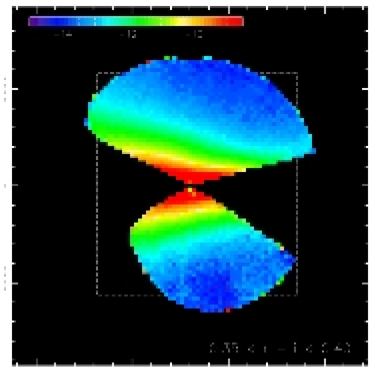


The r-i color bins sample a variety of scales

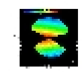
19 r–i color bins – 19 density maps

r - i	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4
D [kpc]	15	13	7	4	3	2	1.5	1
SpT	~F9	G6	K4	K7	M0	M1	M2	M3

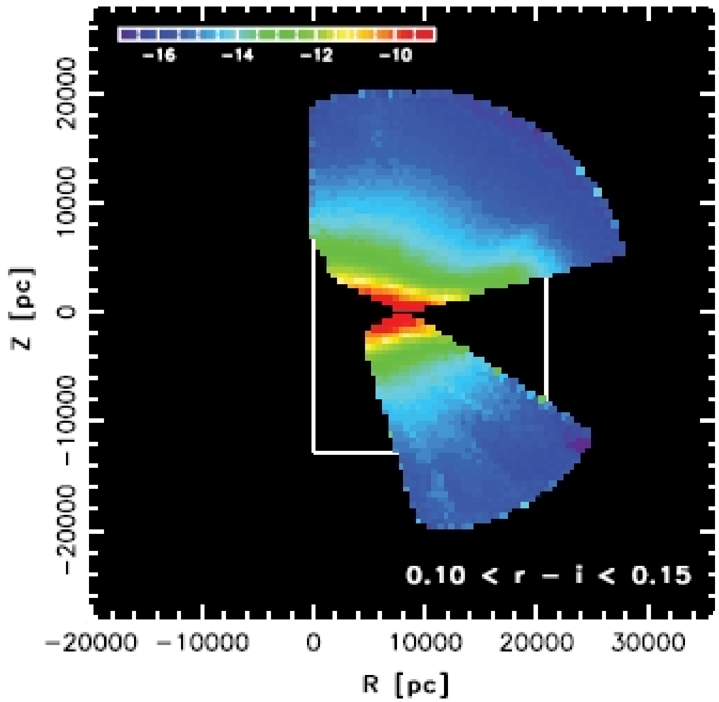


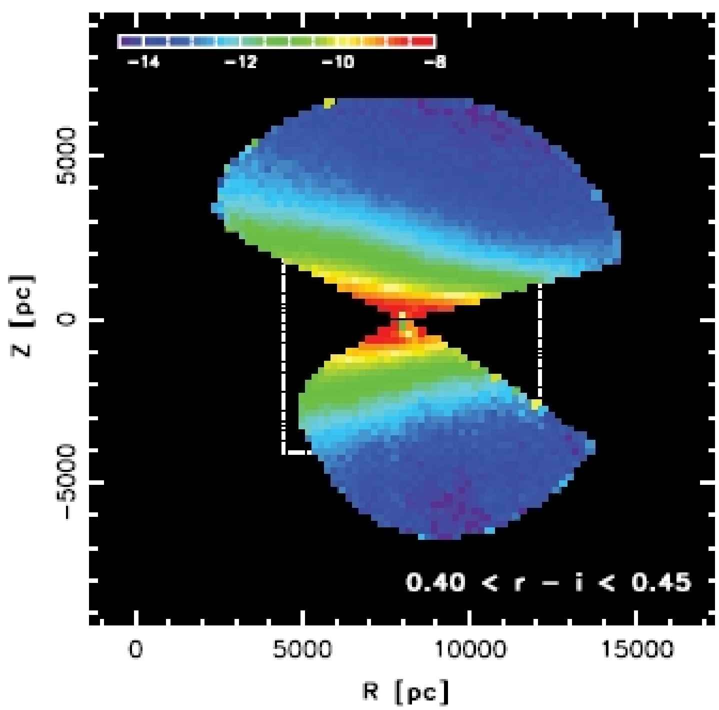


0.35 < r-i < 0.40

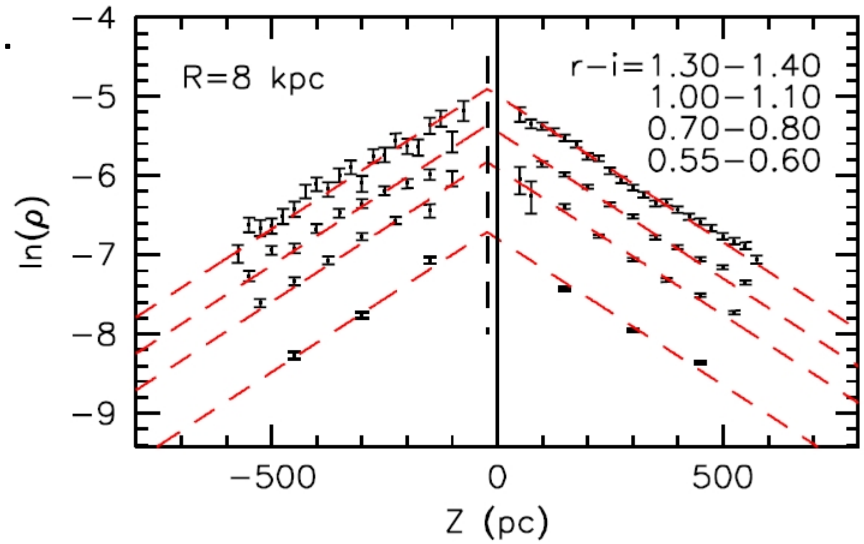


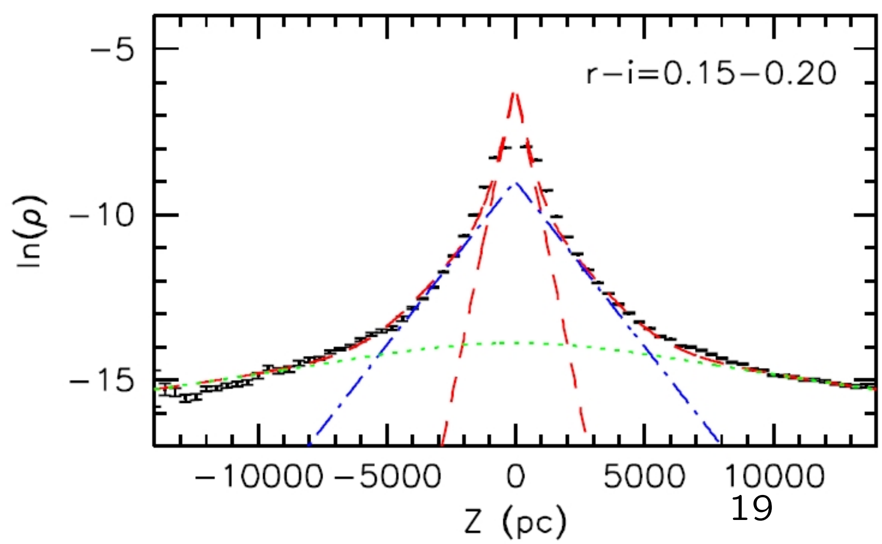
1.3 < r-i < 1.4



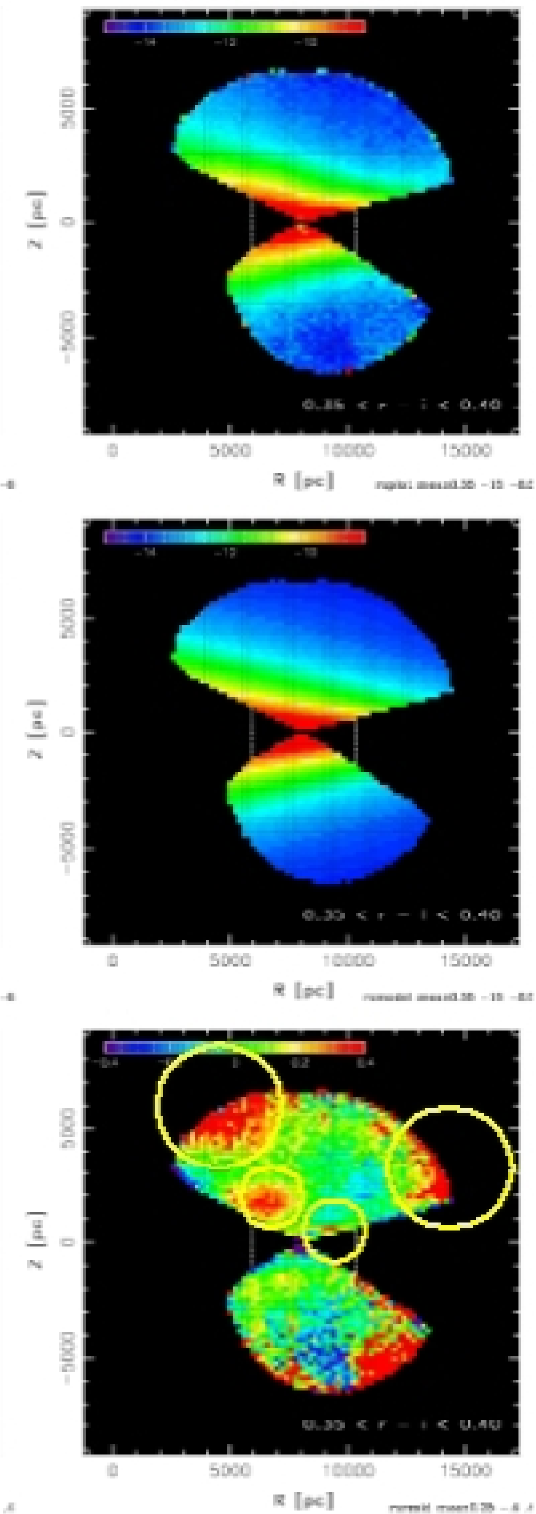


- Jurić et al. 2008 (ApJ 673, 864): unprecedented panoramic view of the Milky Way, akin to observations of external galaxies; with exceedingly high signal-to-noise.





0.35 < r-i < 0.40

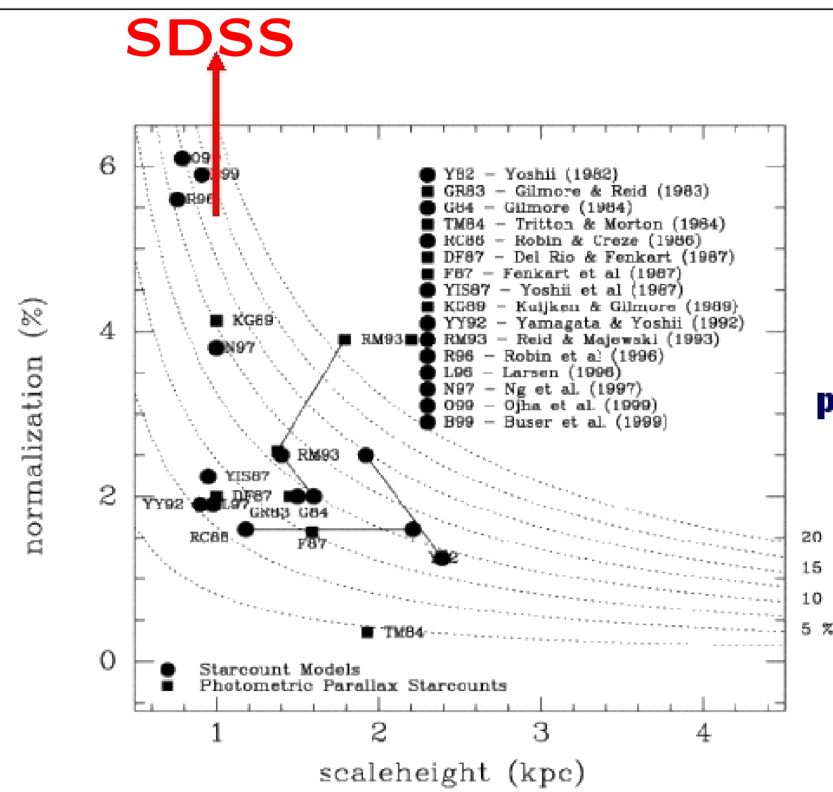


Dissecting the Milky Way with SDSS

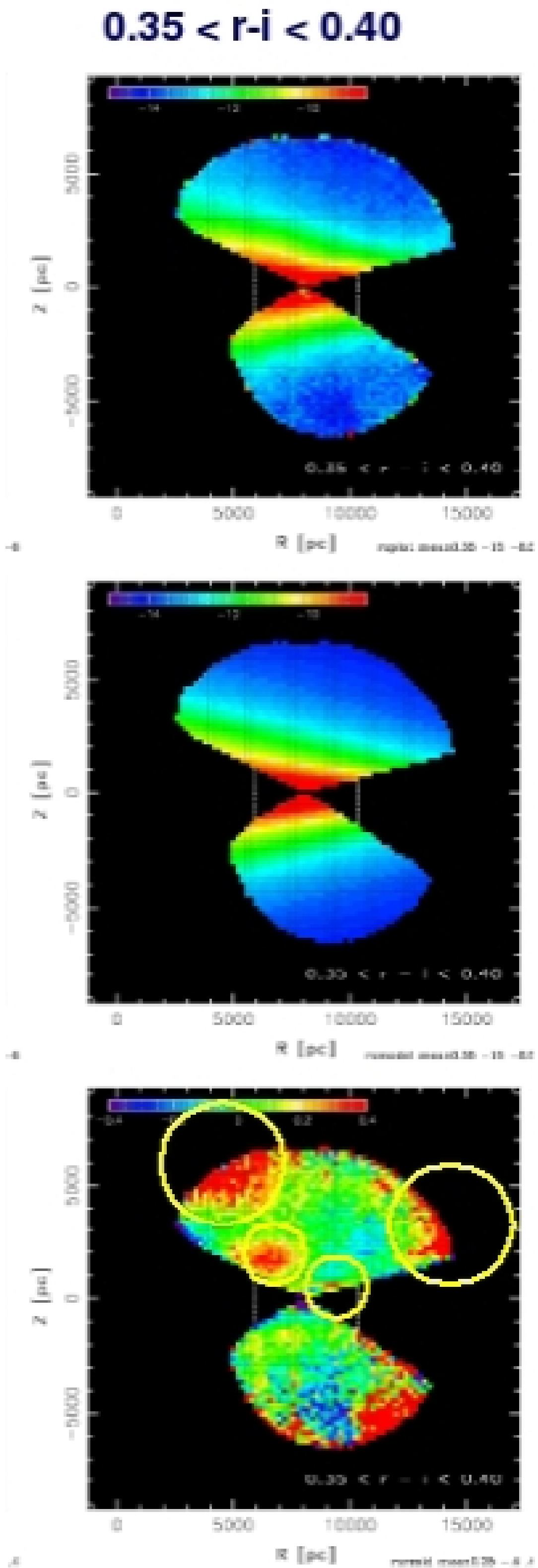
- Panoramic view of the Milky Way: good support for standard Galactic models:

  - Removal of obvious clumps
  - Fit to least "contaminated" bins
  - Exponential disks + halo models

$$\rho(R,Z) = \rho_{thin} e^{-\frac{R-R_e}{l_{thin}} - \frac{|Z+Z_0|}{h_{thin}}} + \rho_{thick} e^{-\frac{R-R_e}{l_{thick}} - \frac{|Z+Z_0|}{h_{thick}}} + \rho_{halo} \left(\frac{R_{GC}}{\sqrt{R^2 + (z+z_0)^2/q^2}} \right)^n$$

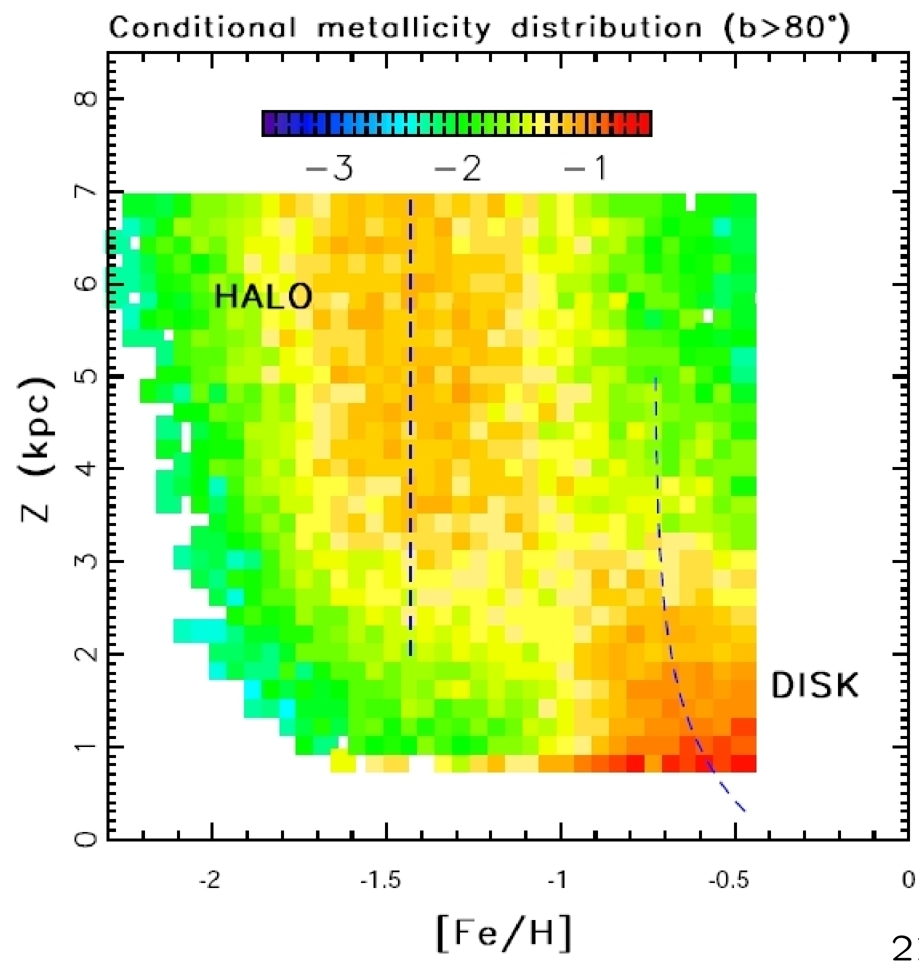


Comparison with prior measurements: SDSS is off scale!

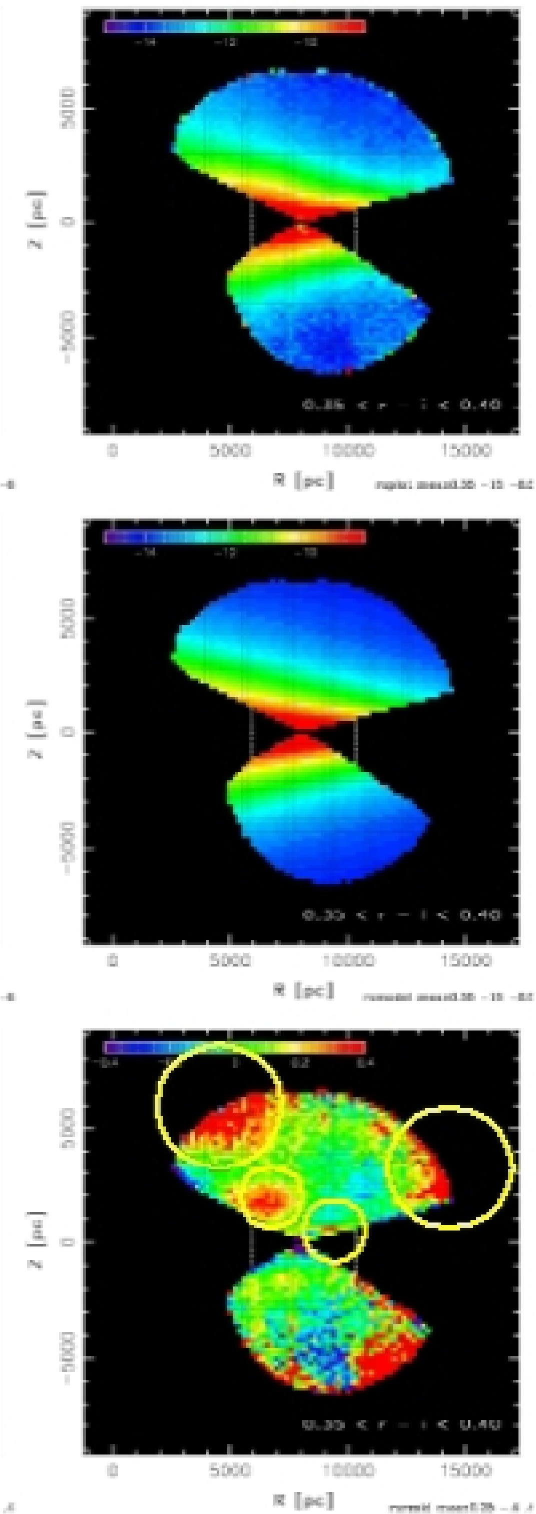


Dissecting the Milky Way with SDSS

- Panoramic view of the Milky Way: good support for standard Galactic models
- Are we overfitting data with two disks and a halo?
- Metallicity mapping supports components inferred from number counts mapping:



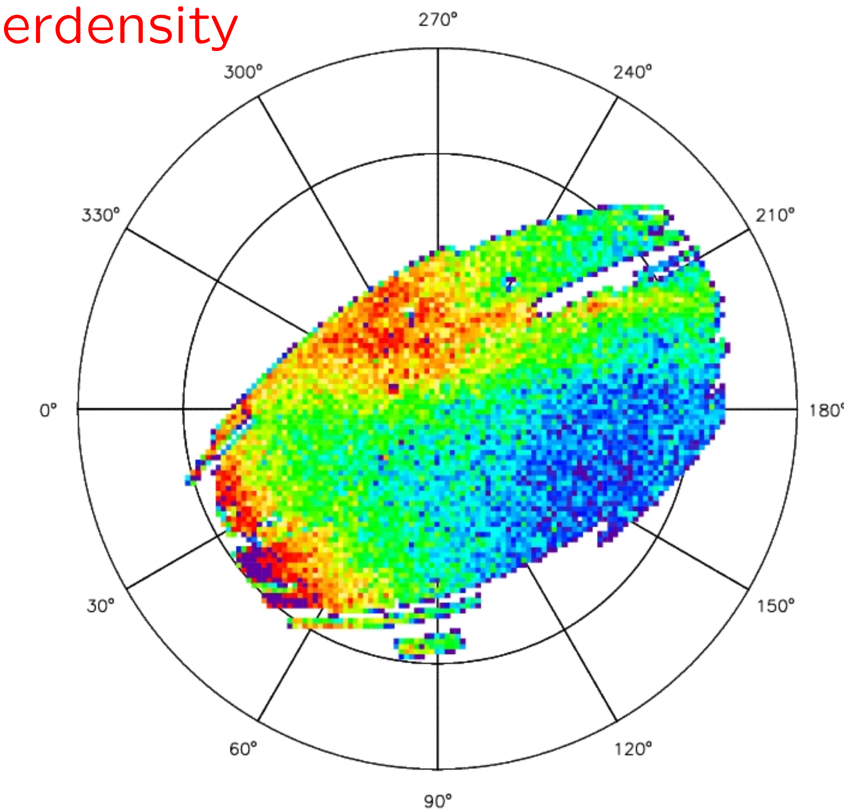
0.35 < r-i < 0.40



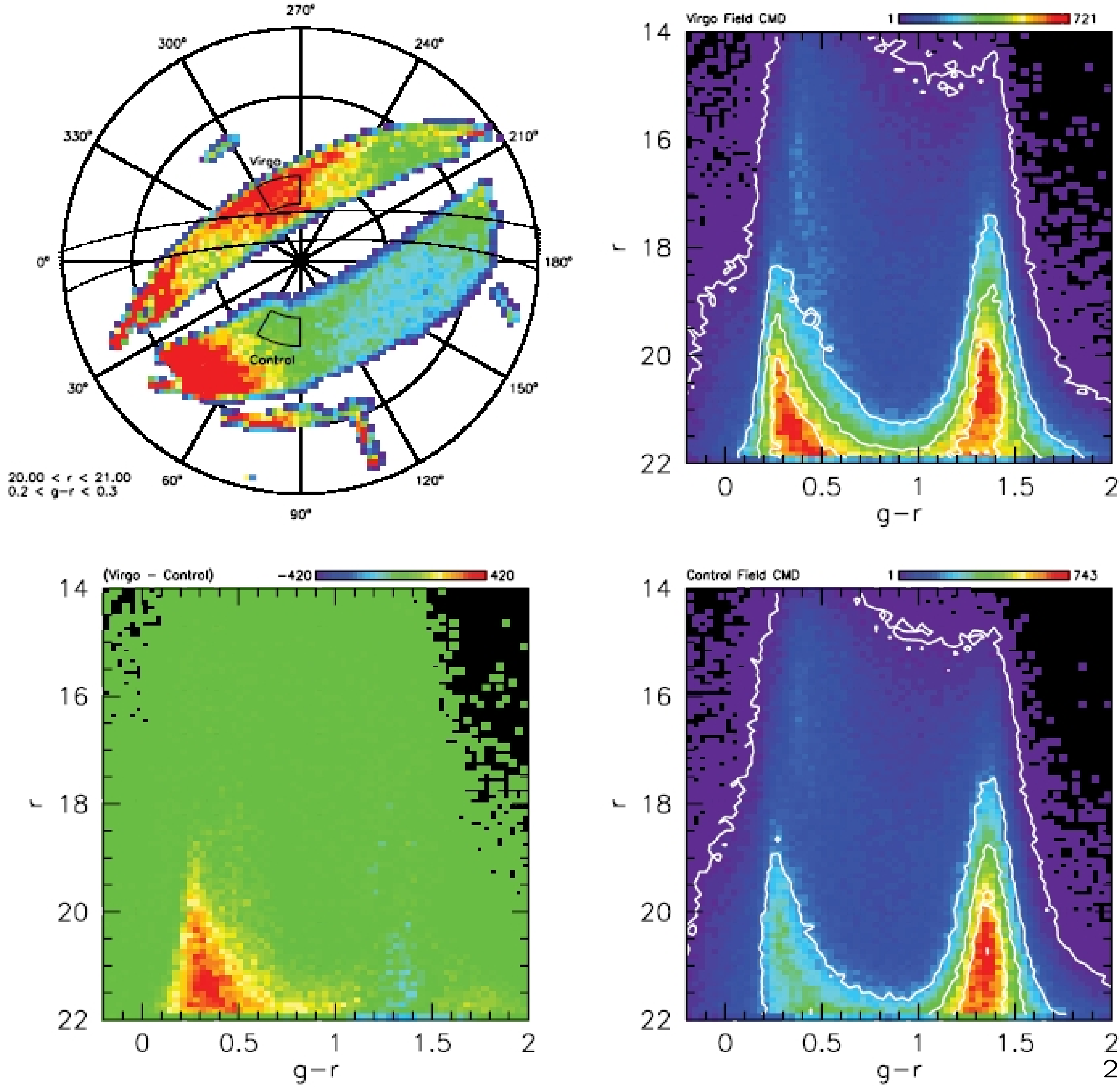
Dissecting the Milky Way with SDSS

- SDSS count maps provide good support for standard Galactic models
- However, the subtraction of (conventional) best-fit model maps from the data maps reveals rich substructure
- The number count excess is typically 20-40% – not easy to see with older data!

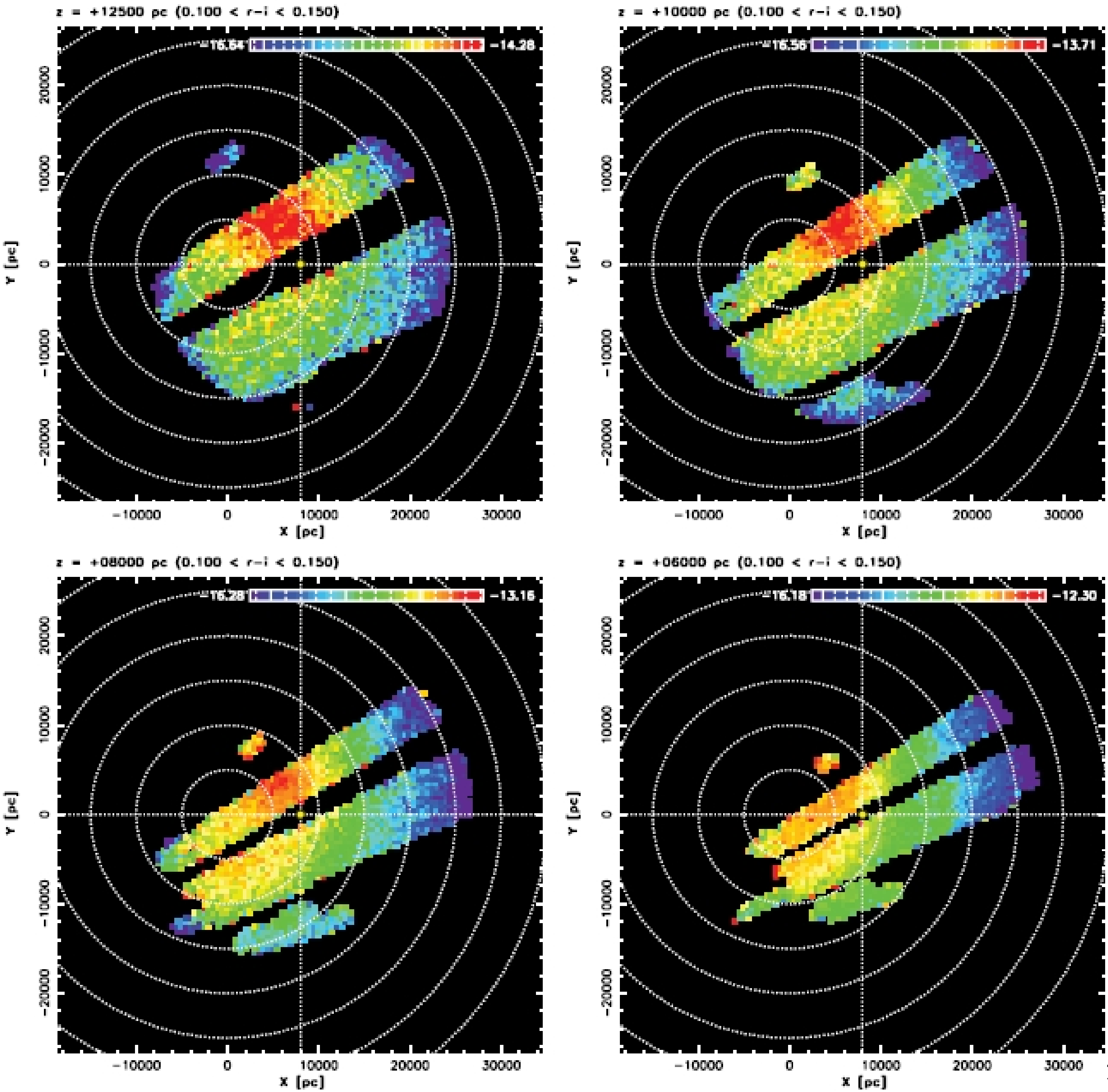
The Virgo overdensity



SDSS DR5: 0.3<g-r<0.4 & 21<r<21.5



270°
300°
240°
330°
210°
Virgo
0°
180°
Control
30°
150°
20.00 < r < 21.00
0.2 < g-r < 0.3
60°
120°
90°
Virgo Field CMD
1
721
r
g-r
(Virgo - Control)
-420
420
Control Field CMD
743



z = +12500 pc (0.100 < r−i < 0.150)
−16.64
−14.28
z = +10000 pc (0.100 < r−i < 0.150)
−16.56
−13.71
z = +08000 pc (0.100 < r−i < 0.150)
−16.28
−13.16
z = +06000 pc (0.100 < r−i < 0.150)
−16.18
−12.30
Y [pc]
X [pc]
−20000
−10000
0
10000
20000
30000

The Virgo Overdensity: the latest news

- "...the Virgo Overdensity ... is best explained by a minor merger." (Bonaca et al. 2012, AJ 143, 105),
- "... a tri-axial dark matter halo is favored and we exclude a prolate shape." (Casey, Keller & Da Costa 2012, AJ 143, 88; figure below is from this paper)

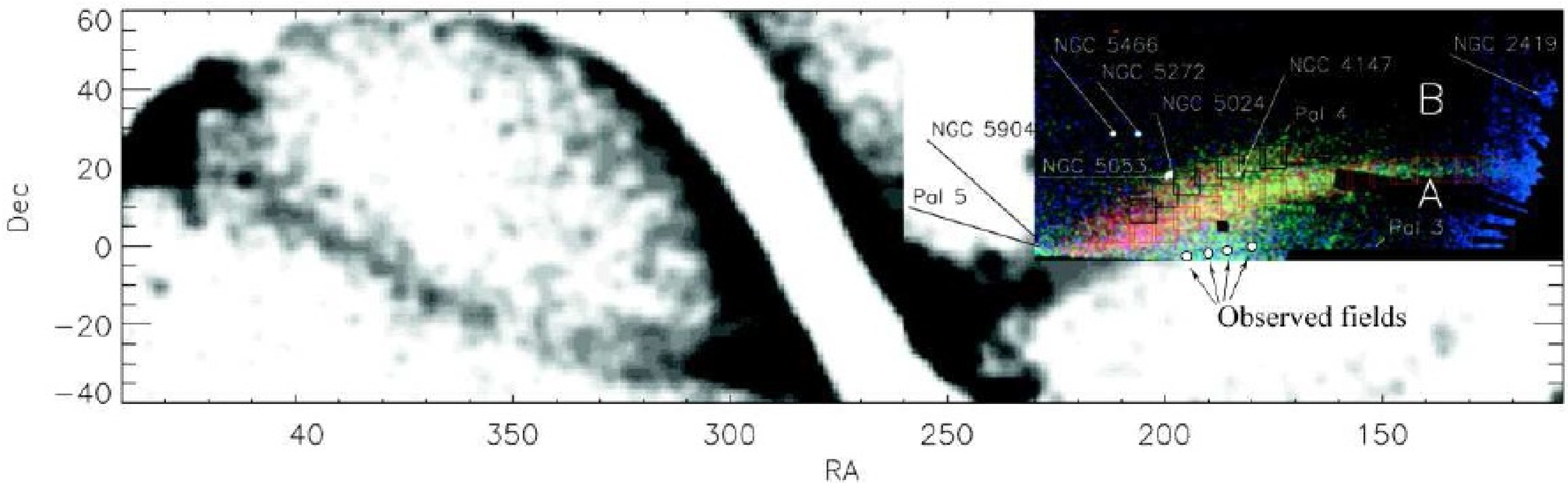
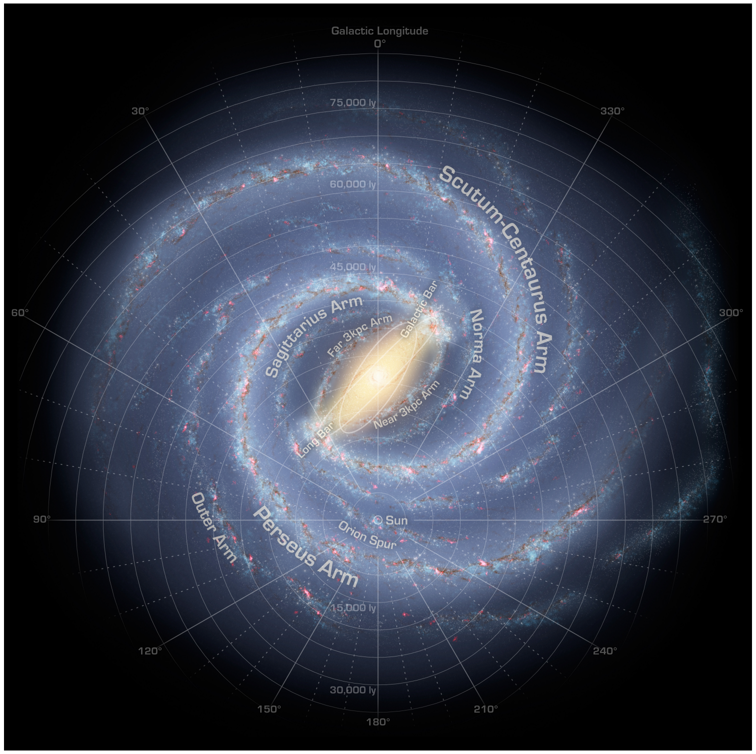
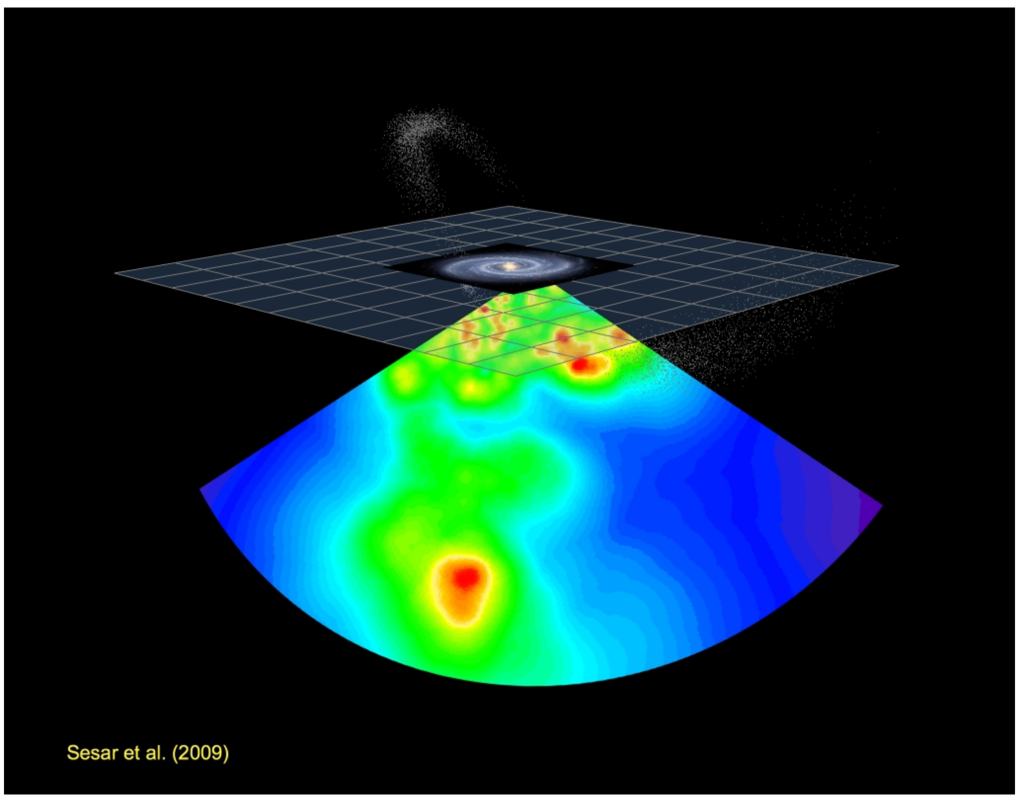


Fig. 5.— Observed fields are outlined upon a panoramic view of the Sgr stream, to demonstrate our field locations in context with the Sgr stream. This plot is an adaptation of Figure 2 in Belokurov et al. (2006), which uses the 2MASS M-giant sample of Majewski et al. (2003).





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 RR Lyrae from SDSS Stripe 82 (Sesar et al. 2010ab, ApJ 708, 717; ApJ 717, 133), 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 $\rho(R) \propto R^{-3}$ out to $\sim$30 kpc, and then becomes steeper.

Summary of SDSS Stellar Count Analysis

- 3D stellar number density maps of the Milky Way from SDSS observations of $\sim$50 million stars; analysis based on photometric distances and thus model-independent

- A two-component exponential disk model is in fair agreement with the data; halo properties, such as power-law index, poorly constrained due to rich substructure and limited sky coverage; however, an oblate halo is always preferred (no strong evidence for triaxial halo)

- A remarkable localized overdensity in the direction of Virgo over at least $\sim$2000 deg^2 of the sky; steepening of the halo profile beyond $\sim$30 kpc

- **Clumps/overdensities/streams are an integral part of Milky Way structure, both of halo and the disk(s)**