The SDSS View of the Milky Way

Mapping the density, metallicity and kinematics of the Galaxy.

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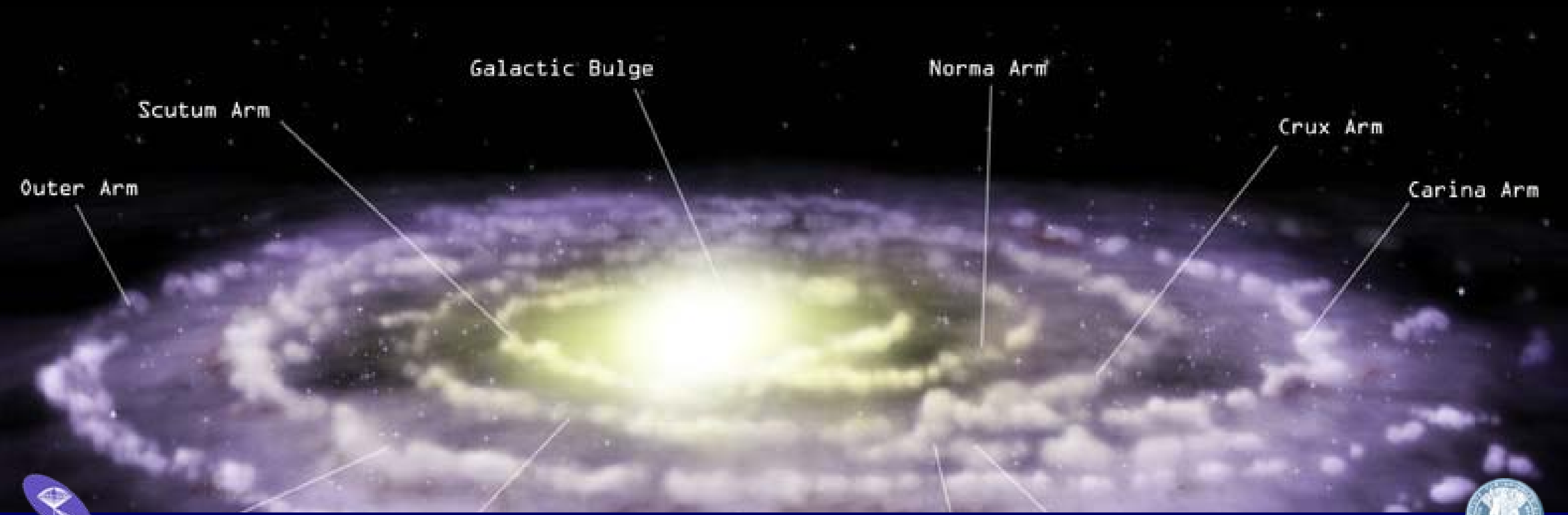
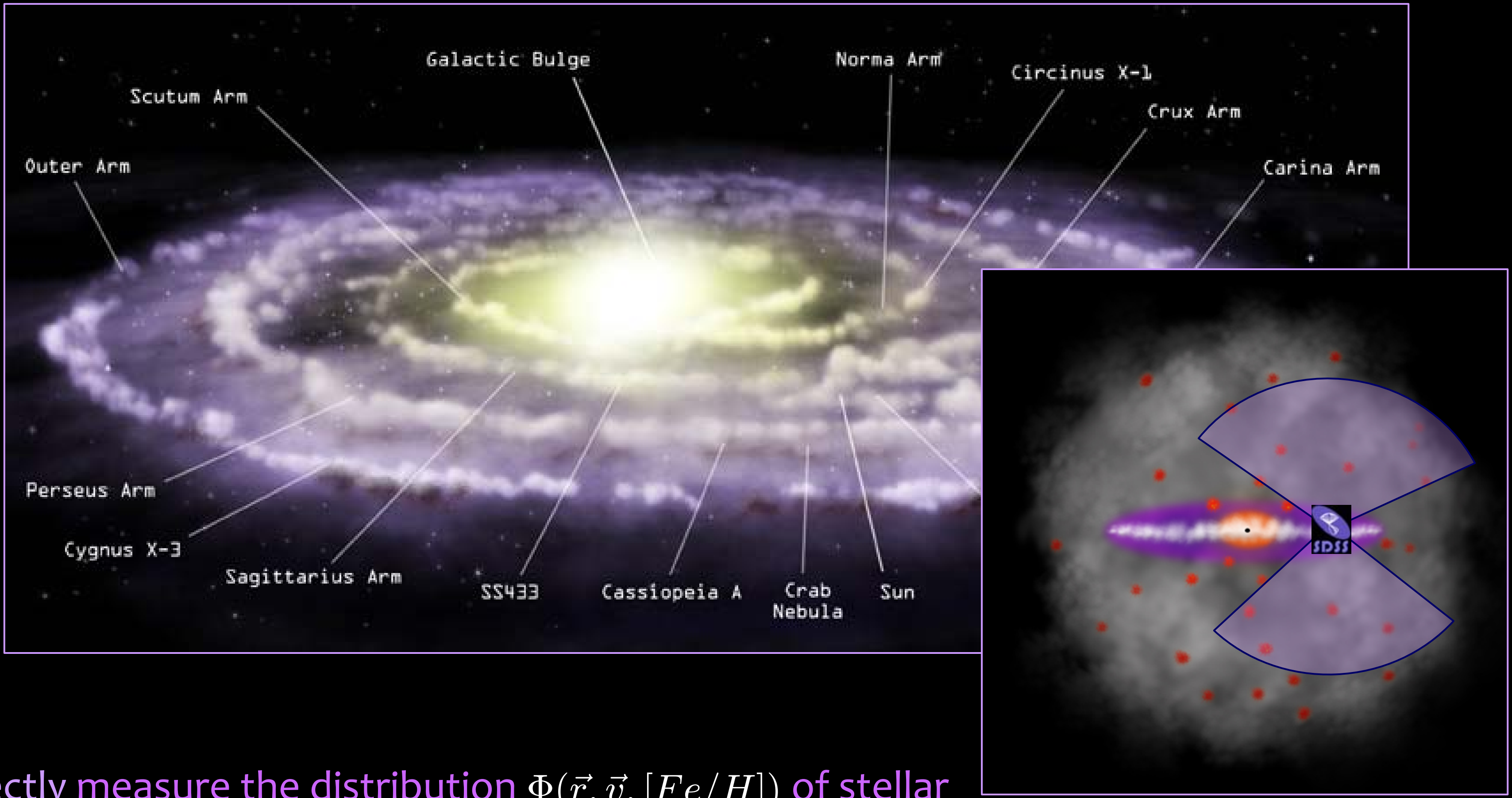
with Zeljko Ivezic, Nick Bond, Branimir Sesar, Robert Lupton… and the SDSS Collaboration



Mapping the Milky Way with SDSS :: Strategy



1. Directly measure the distribution $\Phi(\vec{r}, \vec{v}, [Fe/H])$ of stellar number density, kinematics, and metallicity in a representative volume of the Galaxy.

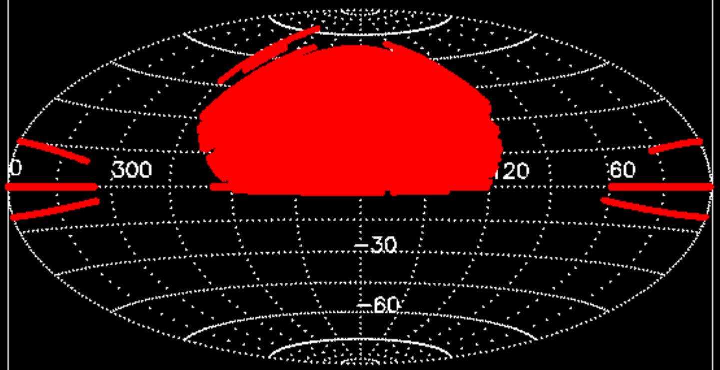
2. Use the distributions to learn about [Gg]alaxy formation, evolution, interactions with environment, and the distribution of dark matter.

Overview

- Part I: Methods
  - Photometric metallicities
  - Photometric distances
  - Proper motions
- Part II: Stars in the Milky Way
  - Distributions of density, metallicity and rotational velocity in the disk and the halo
  - Nearby disk and halo substructure
  - Revisiting the thin/thick dichotomy
  - The nature of the Monoceros stream
- Part III: The future

Sloan Digital Sky Survey

- Imaging and Spectroscopic Survey
  - ~8,000 deg^2 to ~21.5 mag
  - 5 bands (ugriz: UV-IR), 0.02 mag
  - < 0.1 arcsec absolute astrometry
  - ~50M, mostly main sequence, stars
  - R=2000 spectrograph ($390<\lambda/\text{nm}<600$)
    - RV to ~10 km/s
    - Stellar parameters for for >280k stars



SDSS DR6 Imaging Sky Coverage
(Adelman-McCarthy et al. 2008, ApJS, 175, 297)

- An excellent tool for Galactic structure studies
  - Accurate m'band photometry: distance and metallicity estimates
  - Accurate astrometry: proper motions
  - Large area and faint flux limit: representative volume
  - Numerous (MS) stars: reduced uncertainties

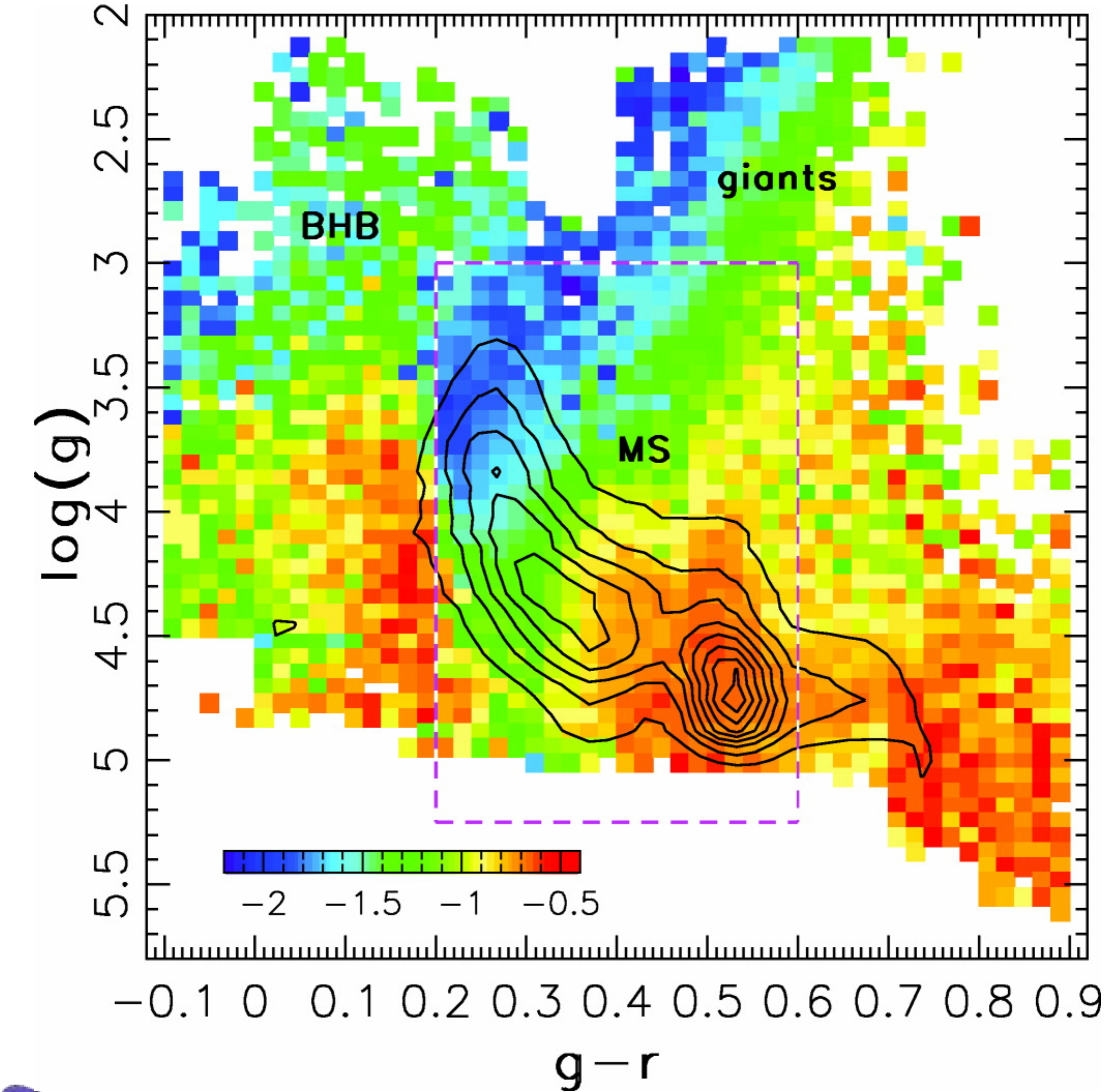
Mapping the Milky Way with SDSS :: Tactics

- Data Reduction:
  - Keeping it simple and clean: *Model-free, 3D* mapping first, modeling second
  - Metallicity: ug,gr + calibration from SDSS spectra
  - Distances: (u)*gri* + photometric parallax relation (r<21.5)
  - Proper Motions / Velocities: SDSS+POSS, SDSS+SDSS
- Output:
  - Distribution of stars in $(X,Y,Z,M_r,[Fe/H],\mu_l,\mu_b)$ space

Part I: Methods

From ugriz,α,δ to X,Y,Z,[Fe/H],Vx,Vy

Stellar parameters: SEGUE Spectra

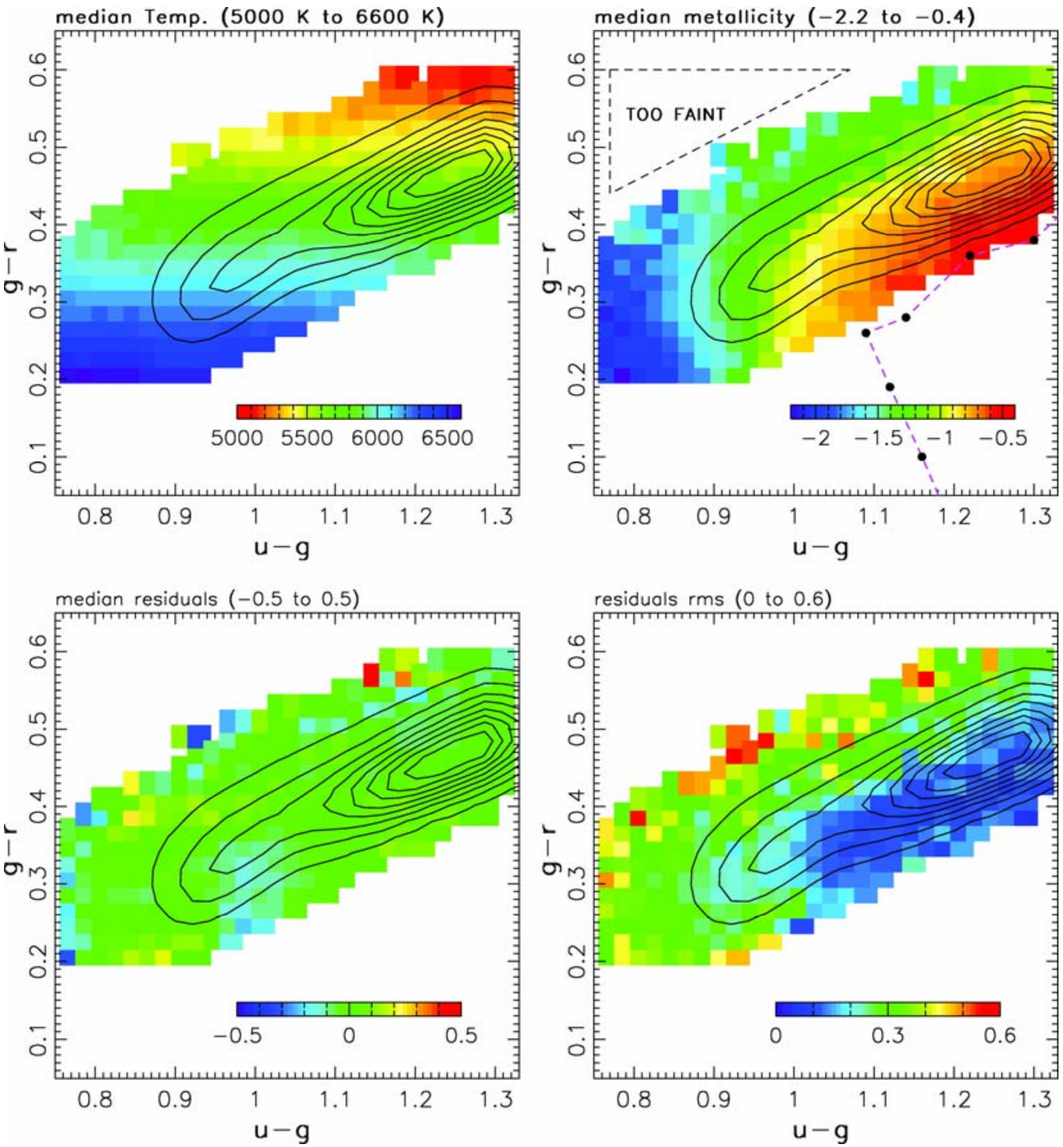


- SEGUE Stellar Parameters Pipeline (Beers et al, Allende Prieto et al. 2006, Lee et al. 2007.)

- σ(Teff) ~ 100K
- σ(log g) ~ 0.25 dex
- σ([Fe/H]) ~ 0.2 dex

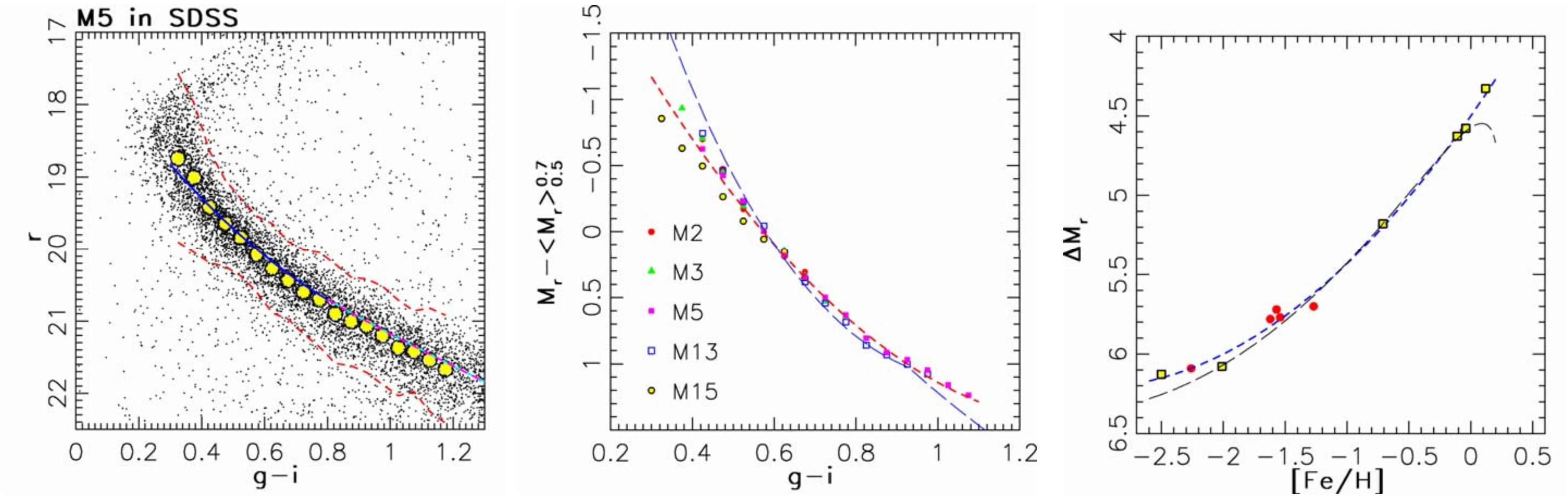
- ~280,000 stars

Photometric Metallicity: Calibration



- (u-g, g-r) colors strongly correlate with spectroscopic metallicity and temperature
- Linear effective temperature fit
- Metallicity:
  - ~f(u-g) only for for g-r < 0.4
  - Depends on g-r for g-r > 0.4
- Precision and accuracy:
  - Teff ~ 100K
  - [Fe/H] ~ 0.09dex (rms, calibration), avg. ~0.2 dex per star (bounded by photometry)
- **Caveat: Works only for g-r < 0.6 (~F through mid-G dwarfs)**

Calibrating the photometric parallax relation



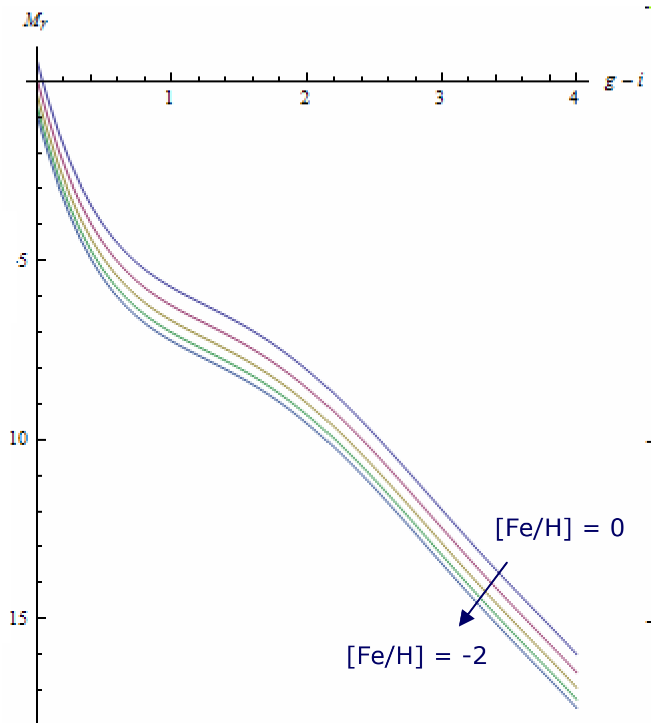
Left: Example of SDSS globular cluster main sequence observation (M5)

Middle: Main sequences of five globular clusters, offset to match for g-i~0.6

Right: The offset needed to produce the right panel (after accounting for different distances), vs. cluster metallicity

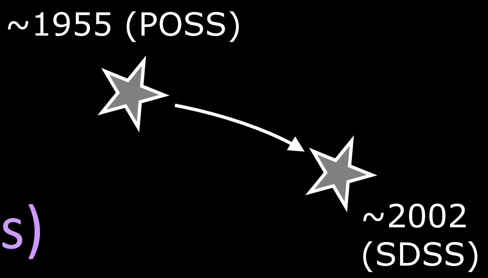
Photometric Parallax

$$\begin{aligned} M_r(gi,0) &= -0.56 + 14.32\,gi - 12.97\,gi^2 + 6.127\,gi^3 - 1.267\,gi^4 + 0.0967\,gi^5 && 0.3 < g-i < 4 \\ \Delta M_r([Fe/H]) &= -1.11[Fe/H] - 0.18[Fe/H]^2 && -2 < [Fe/H] < 0 \end{aligned}$$



1. Metallicity-dependent photometric parallax relation for MS stars
2. Tied to globular clusters on the blue end (g-i<1)
3. Tied to Hipparcos at 1<g-i<2
4. Tied to ground-based trigonometric parallaxes for g-i>2
5. **Distance estimates to better than 15% (likely better than 10% on the blue/bright end)**
6. **Directly applicable to any (u)gri survey (PanSTARRS, SkyMapper, DES, LSST, …)**

Proper Motions

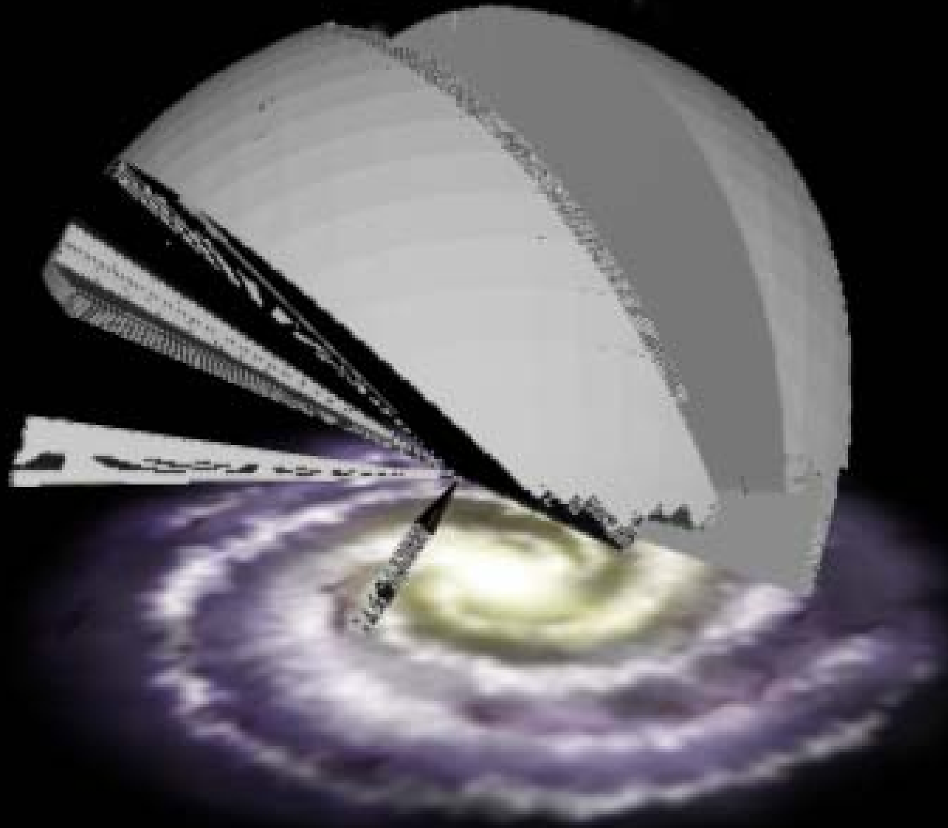


- Munn et al (2004, 2008)
  - Recalibrated POSS astrometry (w. galaxies)
  - Errors:
    - Random: 3 mas/yr to r < 18, 6 mas/yr at r=20
    - Systematic: ~0.3 mas/yr (using 100k quasars)
  - Publicly available as part of DR6
  - Over 30M main sequence stars, entire SDSS footprint

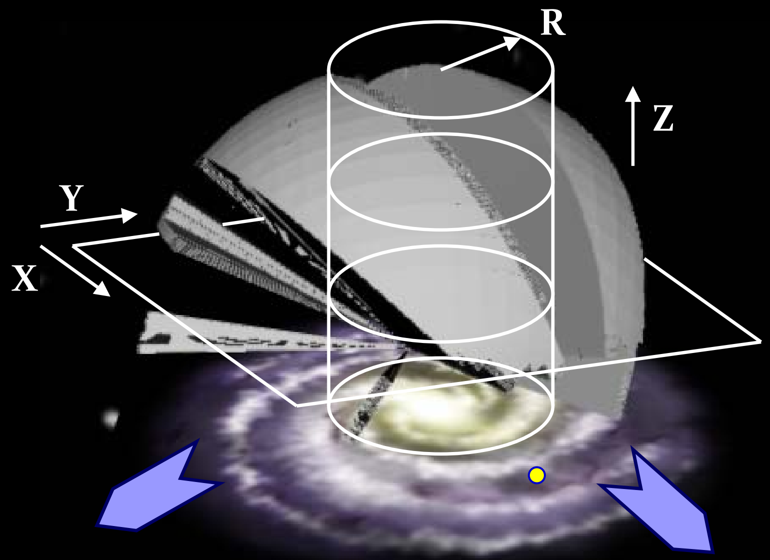
- DR6 sample ($D_{max} \sim 10$ kpc)

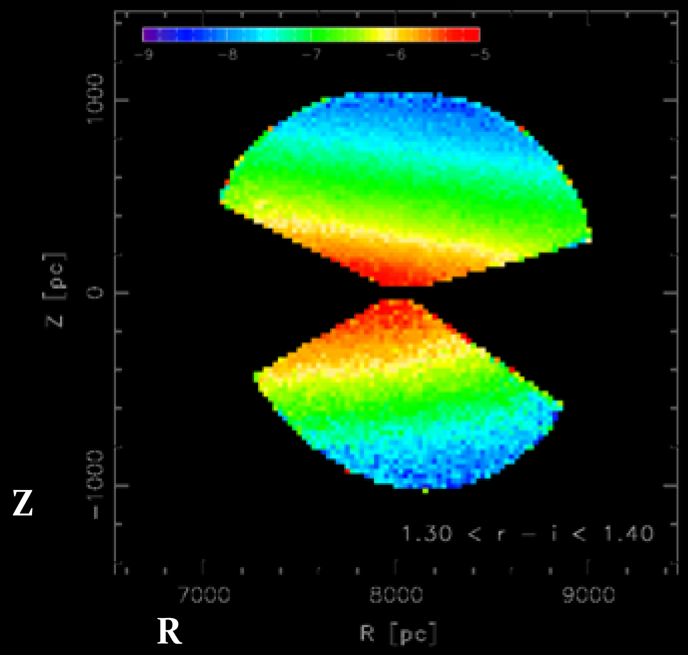
Mapping the Milky Way

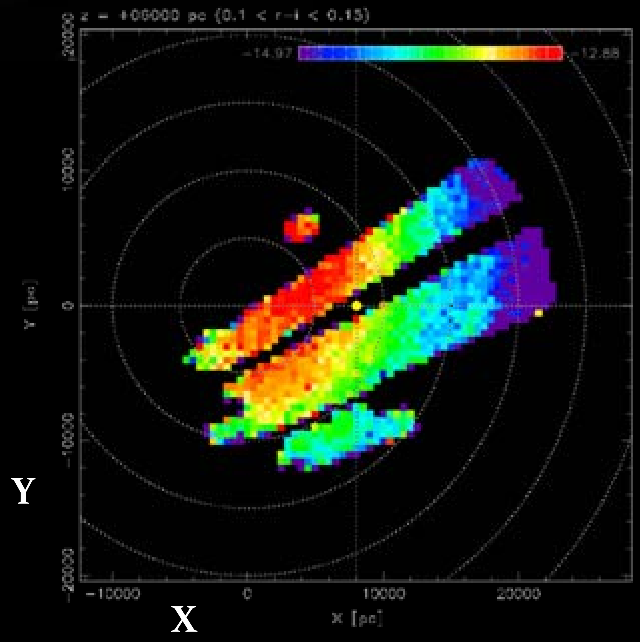
ρ, [Fe/H], μ_l, μ_b



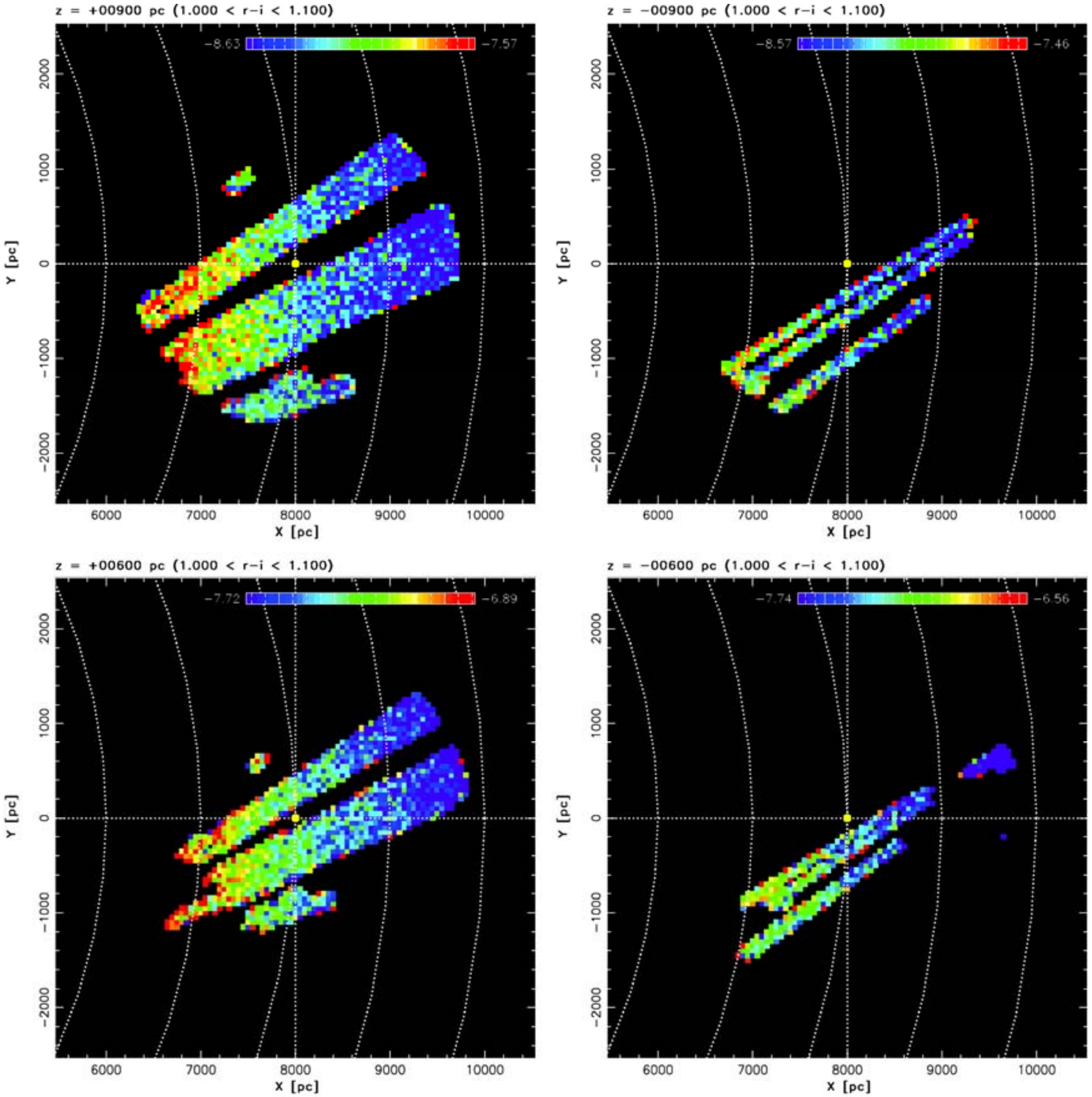
Dissecting the datacube



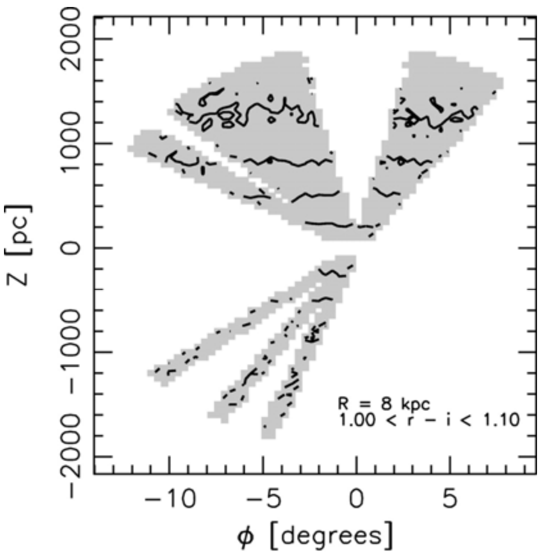




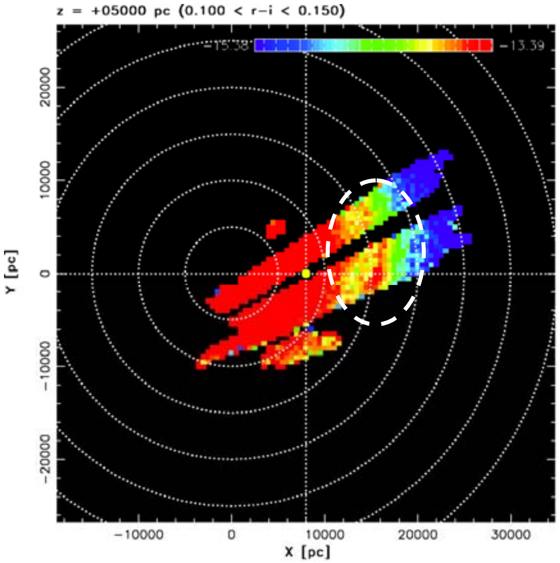
Density Maps: D < 3kpc (Late K, M stars)

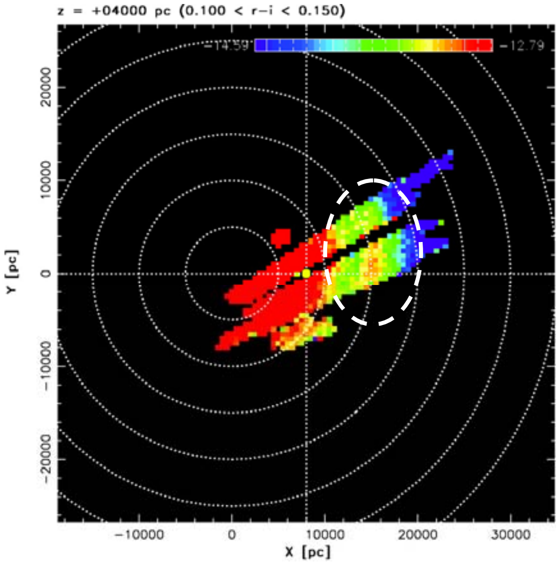


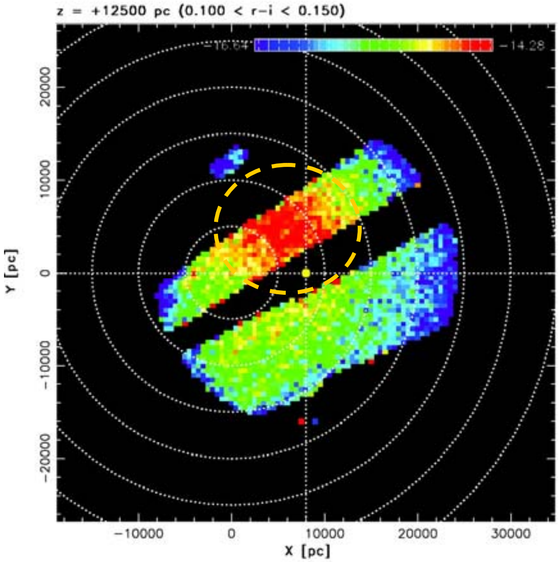
- Right: X-Y maps of number density distribution at Z=+/-900 and +/-600 pc for 1 < r-i < 1.1 stars (~M dwarfs)
- "Face-on view" of the Galaxy
- Bottom: Density contours around the axis of symmetry

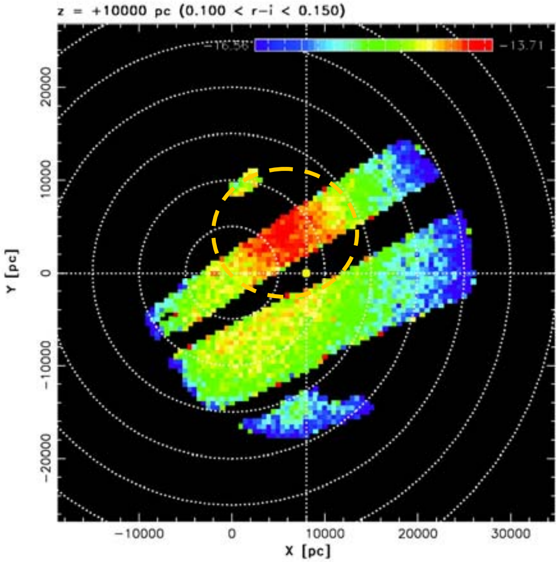


Density Maps: D > 3kpc (F, G, early K)



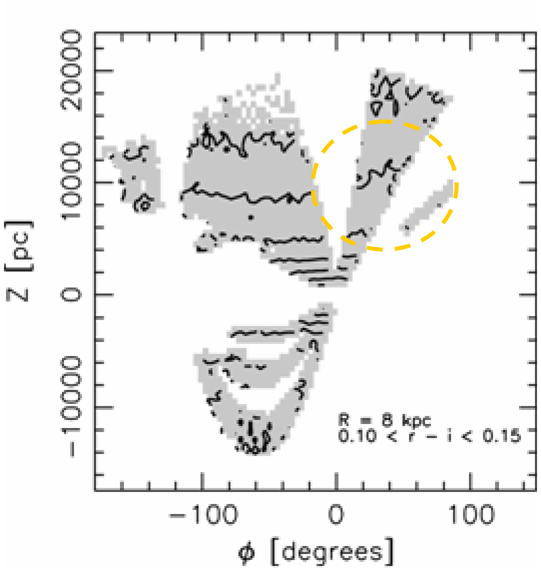




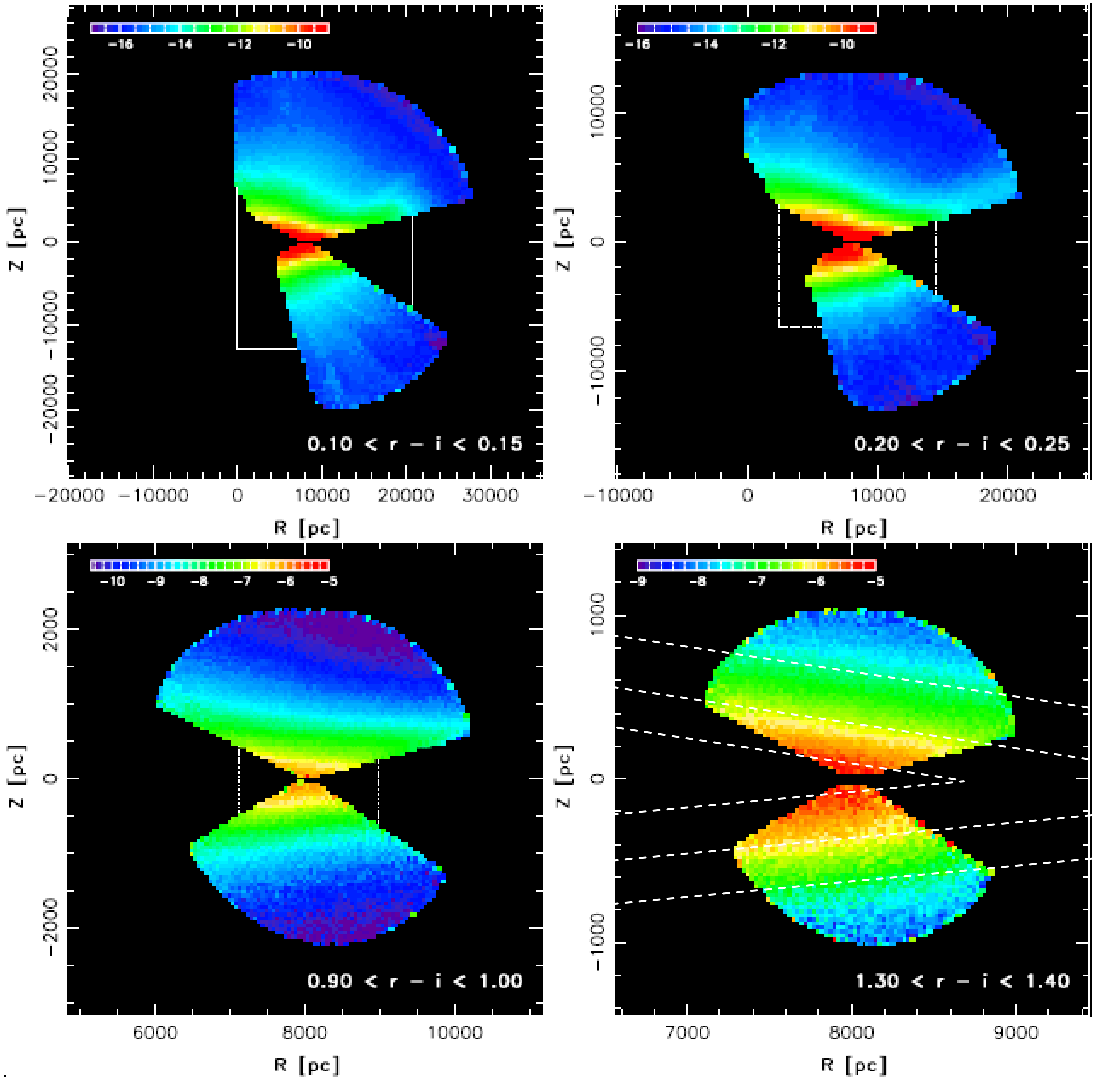


- Right: X-Y maps of number density distribution at Z=5, 4, 12, 10 kpc for .1 < r-i < .15 stars (~F/G SpT)

- Signatures of overdensities



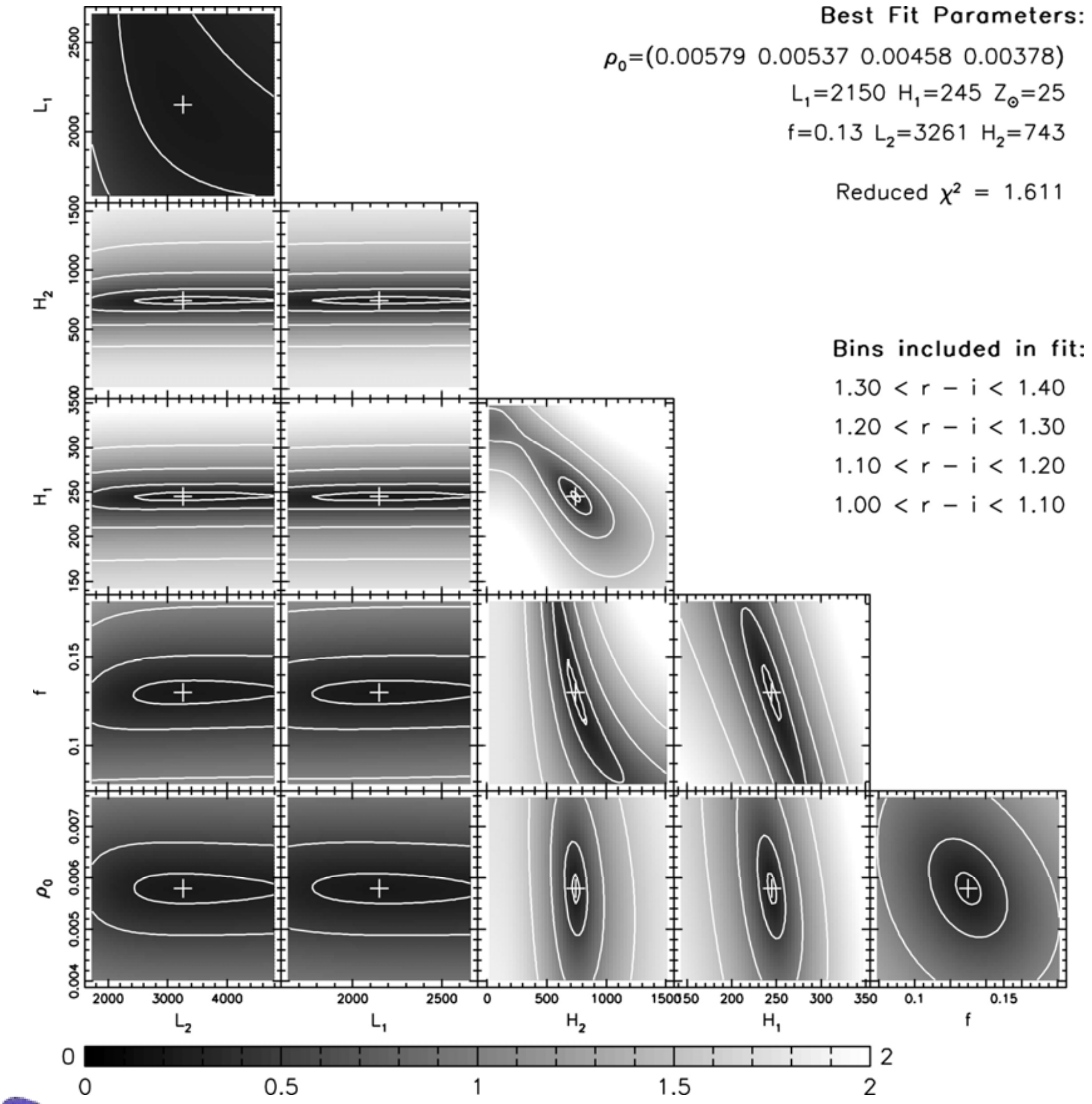
Edge-on View (R-Z density distribution)



- Right: $\phi(R, Z)$ density distribution (“edge-on view”)
- 1 kpc (bottom right; M dwarfs) to ~20kpc (top left; F dwarfs) scales

- **Map Analysis Summary:**
  - **Smooth, axisymmetric, background consistent with exponentials (disk) and power laws (halo)**
  - **Overlaid by localized overdensities: clumps and streams**
  - **Most major overdensities at D > 3kpc**

Disk Model Fit



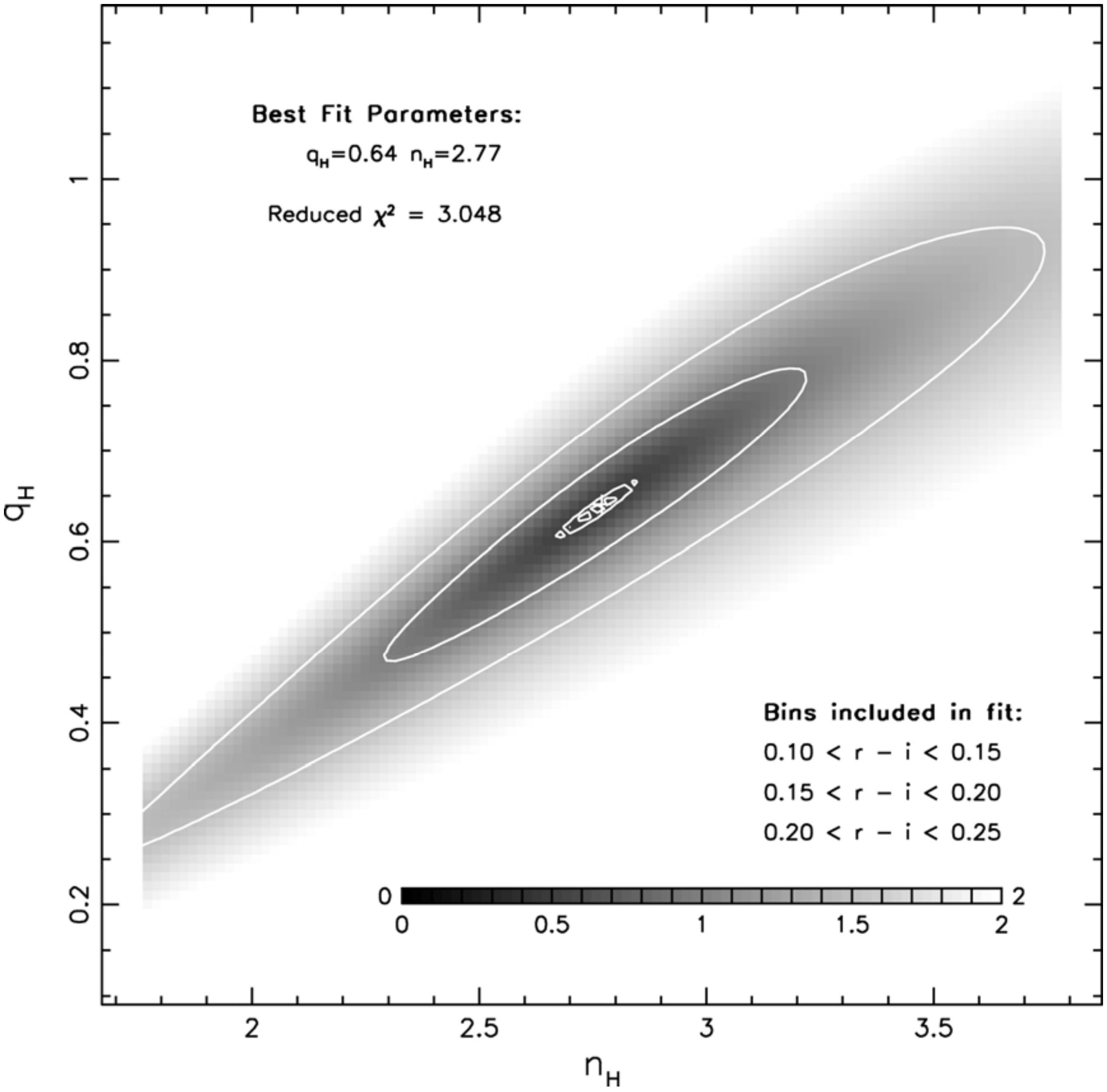
- M-dwarfs (D < 2 kpc) excellently fit by two exponentials

- Best fit:
    - $Z_0 = 25$ pc
    - $H_1=245$ pc, $H_2=740$ pc
    - $L_1=2.15$ kpc, $L_2=3.3$ kpc
    - $f=13\%$
    - Reduced $\chi^2=1.6$

- Uncertainties and covariances easily seen in χ^2 plots (left)

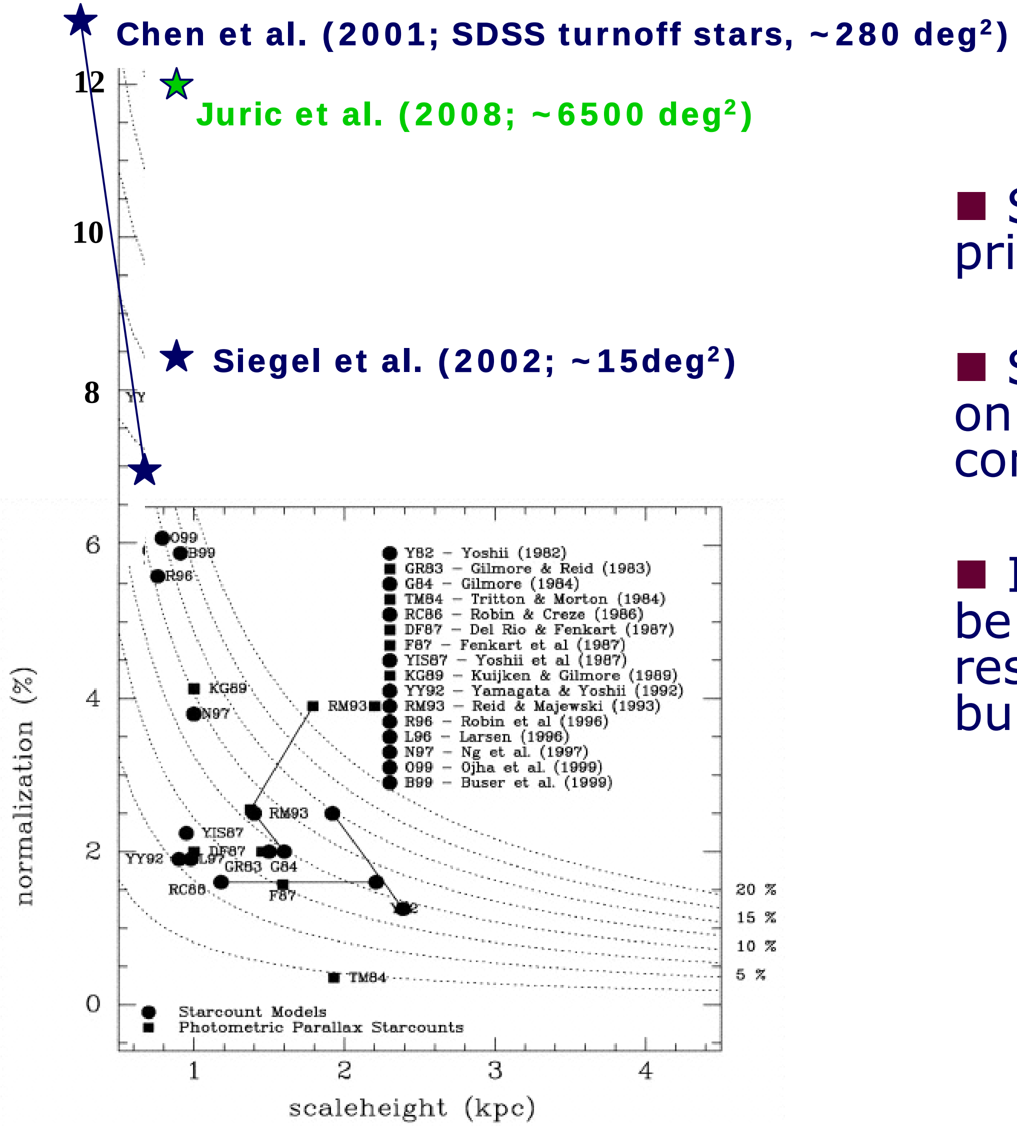
- Same values obtained when allowing the scales to vary in adjacent color bins

Halo Fits



- 10kpc < D < 20kpc
- Power law
  - $n_H = 2.8$
- Clearly aspherical, oblate
  - $q_H = 0.6$
- Normalization: $f_H = 0.5\%$,
- Poorer fit (reduced $\chi^2 \sim 3$)
  - Indicative of large scale departures from simple power law (dual halo)
  - Or clumpiness of the halo (Bell et al. 2008)

Why do you care?


Chen et al. (2001; SDSS turnoff stars, ~280 deg^2)

Juric et al. (2008; ~6500 deg^2)

Siegel et al. (2002; ~15deg^2)

- Significant disagreement in prior measurements

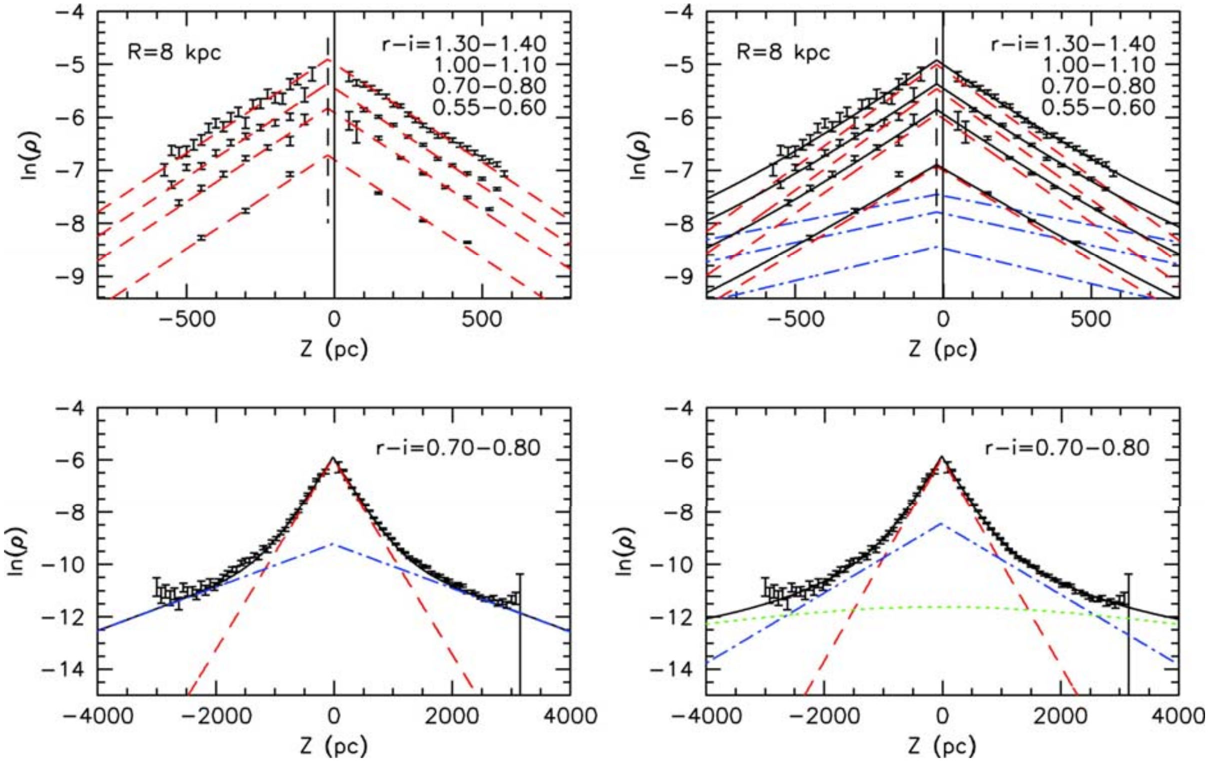
- Significant disagreements on the percentage of mass contained in the thick disk

- IMPORTANT, as the fits will be EXTRAPOLATED to the rest of the Galaxy when building dynamical models

"Galactic Structure and Structure of Galaxies", Ensenda, Mexico

The Value of Wide Area I: Breaking the Degeneracy

- NGP line of sight only:



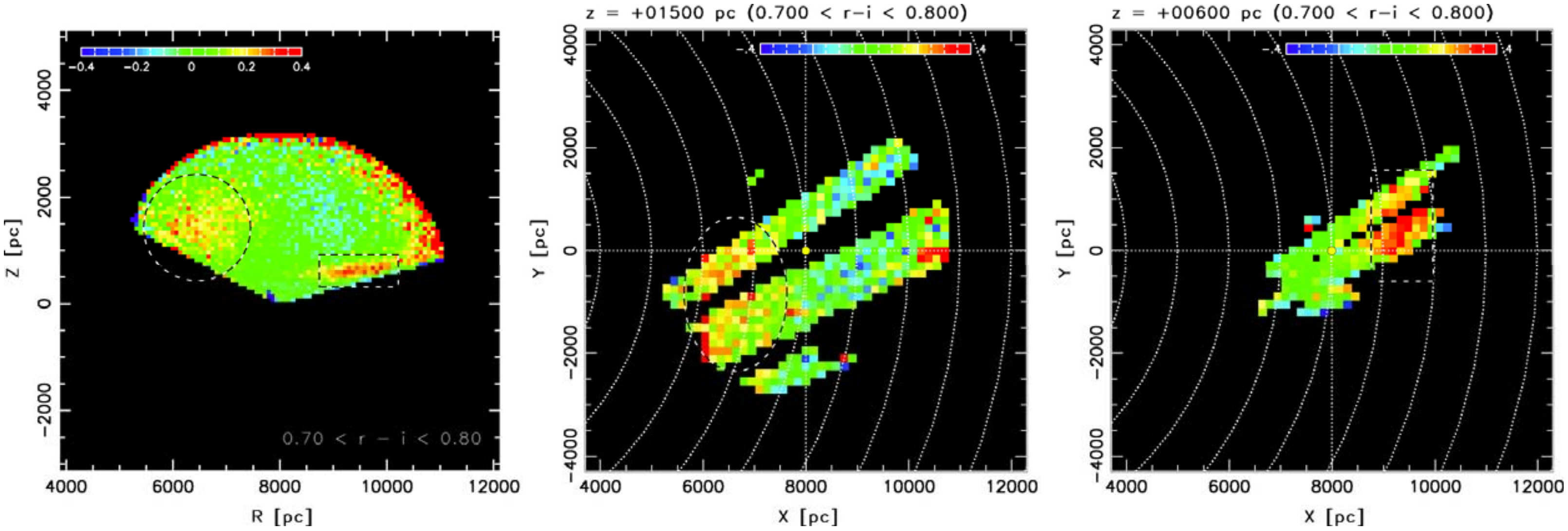
- H_1=260pc
- H_2=1000pc
- f=4%

- H_1=245pc
- H_2=750pc
- f=13%

- Two substantially different fits describe the NGP line of sight equally well
- A number of prior studies are NGP-only
- Wide area survey is necessary to break the degeneracy

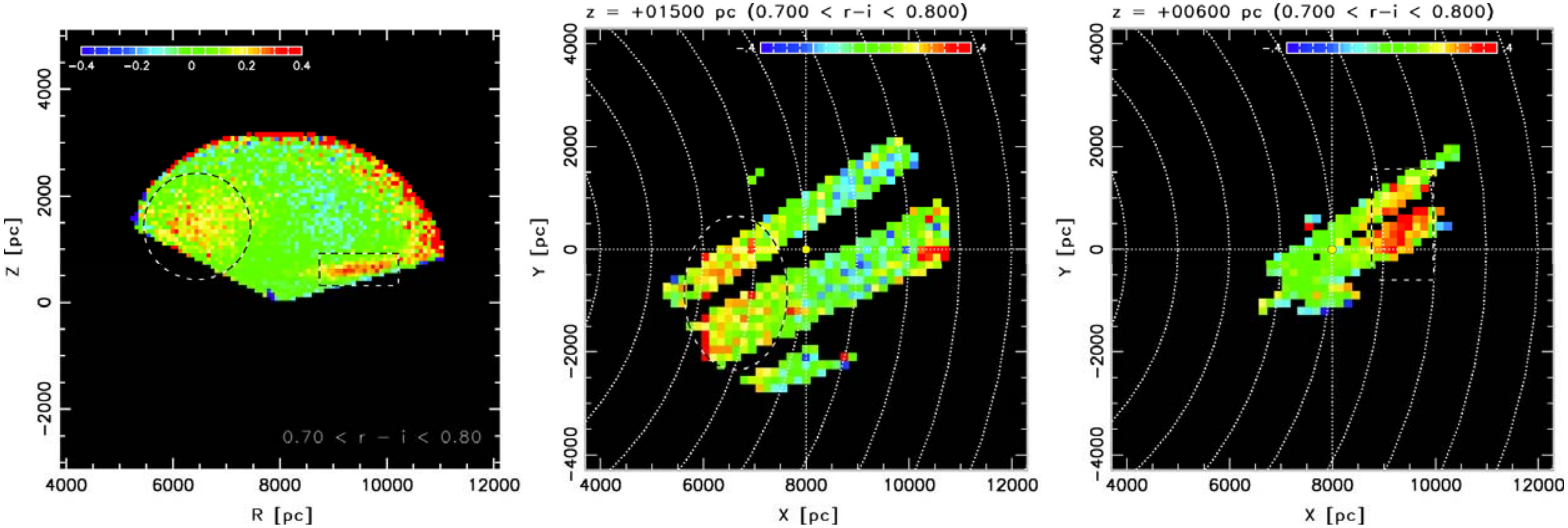
- In our case, the fit always converged to the same minimum (or did not converge at all)

The Value of Wide Area II: Seeing/Avoiding the Substructure



- Vermin of the Galaxy
- If unrecognized, overdensities will influence the fits
- The only way to identify them is with a wide area survey

Disk substructure



- Monoceros stream (Newberg et al. 2002; not shown here, more later)

- Two additional disk substructures (follow-up under way)
  - R=6.5kpc, Z=1.5kpc: ~20% over the background
    - “Thick disk asymmetry” of Larsen & Humphreys (1996)
  - R=9.5kpc, Z=0.8kpc: ~50% over the background
    - Faint kinematic/metallicity signature (Bond et al., in prep)

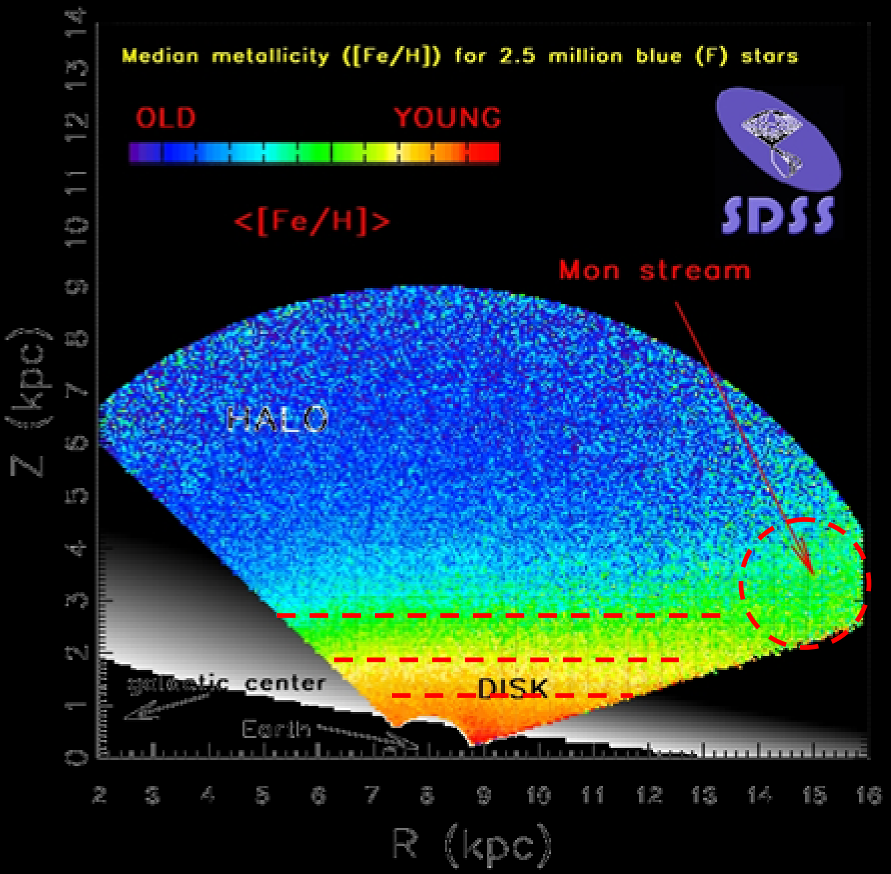
Story so far

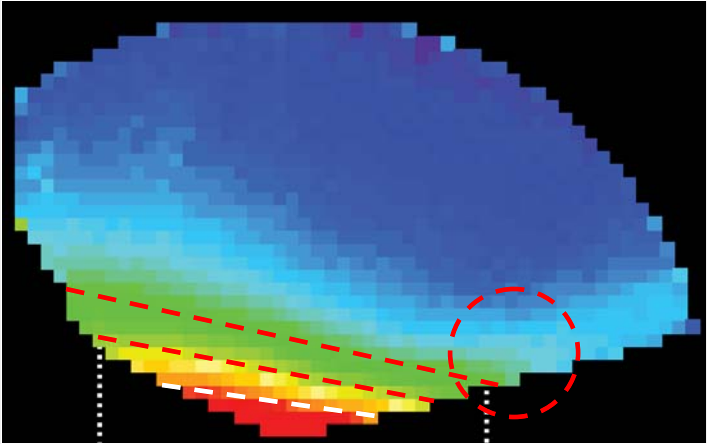
- Precise mapping of galactic density distribution in ~1/4 of the sky, to 50pc-15kpc
- Smooth, exponential distribution, accounts for >97% of the stellar mass in the observed volume
- Explanation of discrepancies in prior results
  - Degeneracy, substructure
- Detection of substructure in the disk
  - Extrapolation to the whole disk: 20-40 similar substructures

Dissecting the Milky Way:
Metallicity

Metallicity Map

Ivezic et al. (2008)





- Metallicity does not follow density
- Features in density space ↔ features in metallicity space

Disappearance of radial metallicity gradient – radial migration?

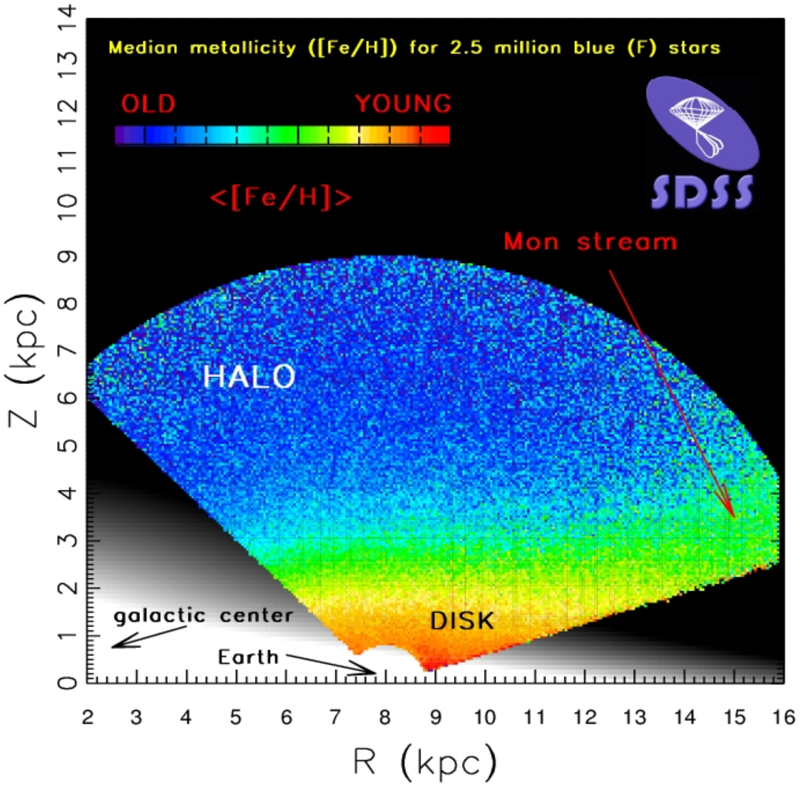
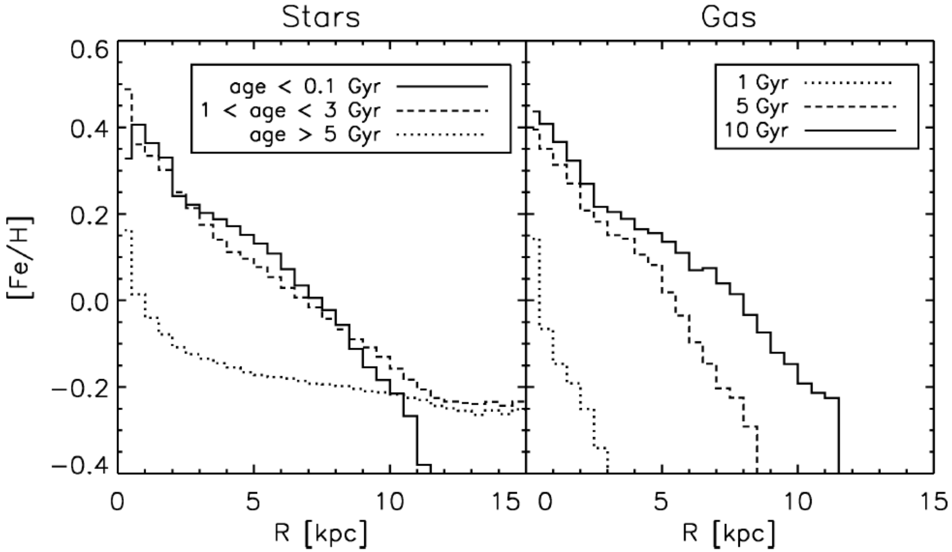


Figure 2. from Roškar et al. (2008)

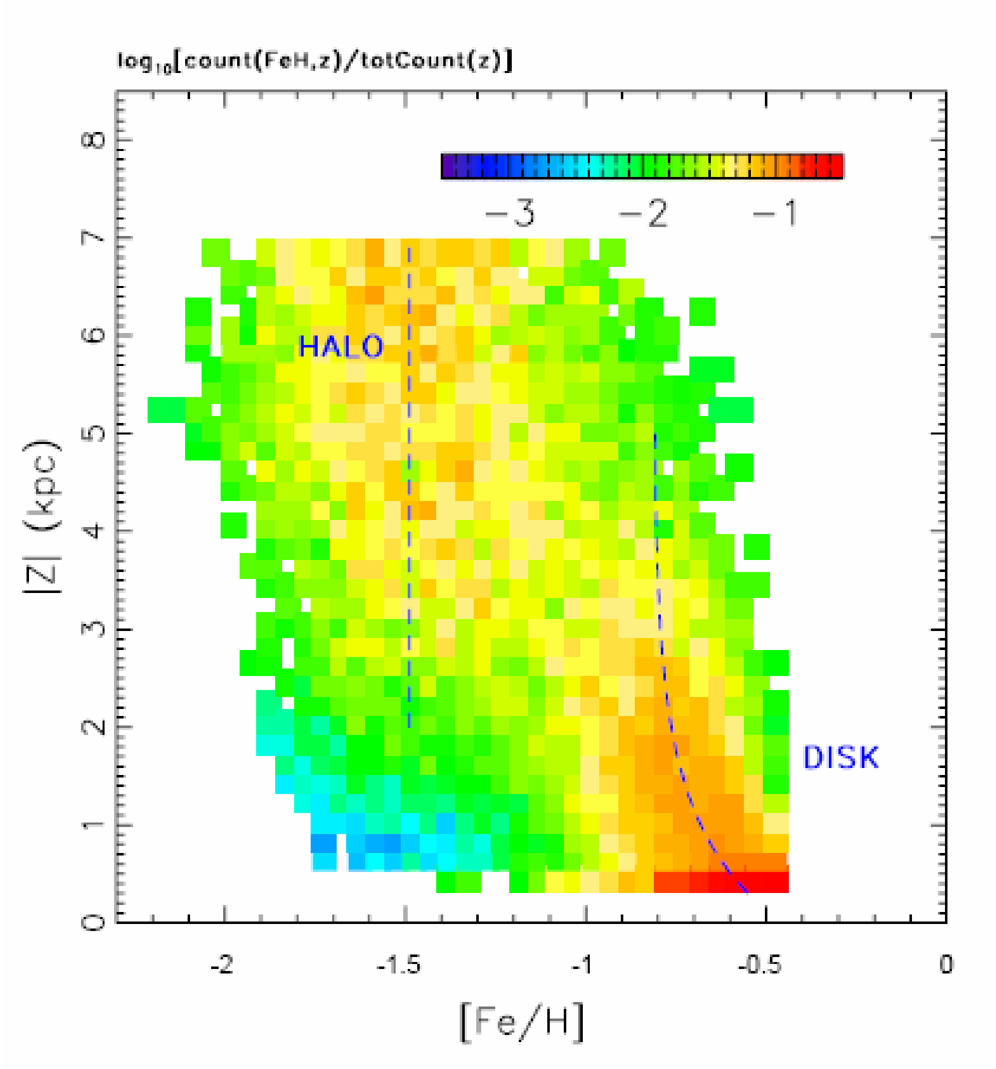


Young stars: low vertical velocity dispersion, closer to the plane, strong radial gradient reflecting the local ISM (R08)

Old stars: high vertical dispersions, extend high above the plane, shallower gradient due to radial mixing (R08)

Net effect: The observed disappearance of radial gradient out of the plane

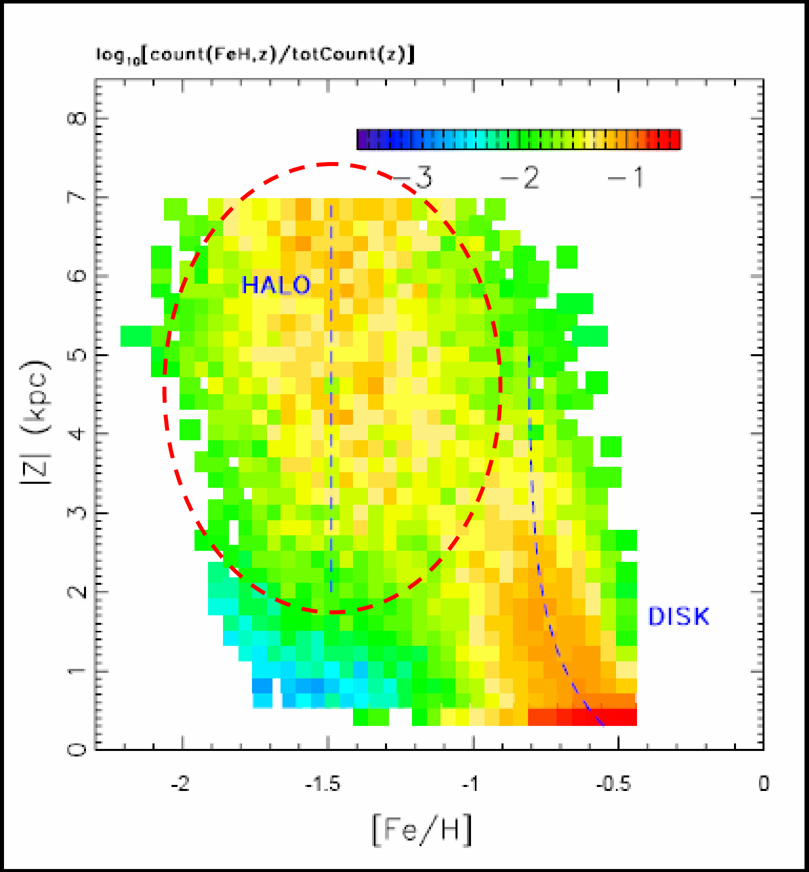
Vertical Variation of Metallicity Distribution Function



1) Clear disk/halo separation
2) Vertical metallicity gradient in the disk

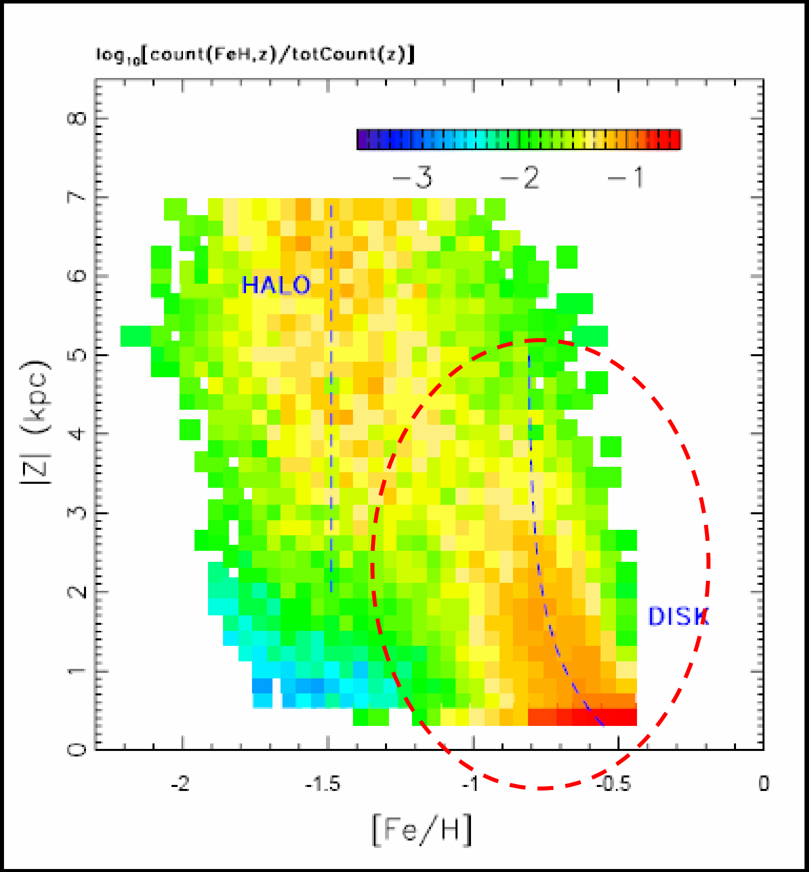
Mario Juric <mjuric@ias.edu>, Thursday, October 2nd, 2008.
"Back to the Galaxy II", KITP, Santa Barbara, CA

Halo MDF



- Halo Model:
  - Well described by a Gaussian metallicity distribution
  - μ = -1.46 dex
  - σ = 0.3 dex
  - Mean and dispersion independent of position

Disk MDF



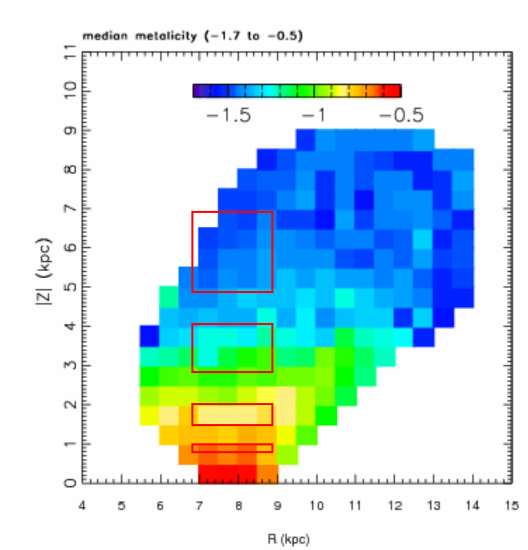
- Detection of metallicity gradient

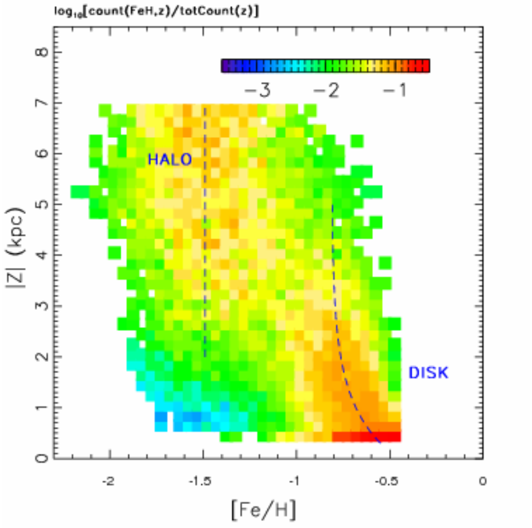
$$\mu_D(Z) = \mu_\infty + \Delta_\mu \exp(-|Z|/H_\mu) \text{ dex}$$

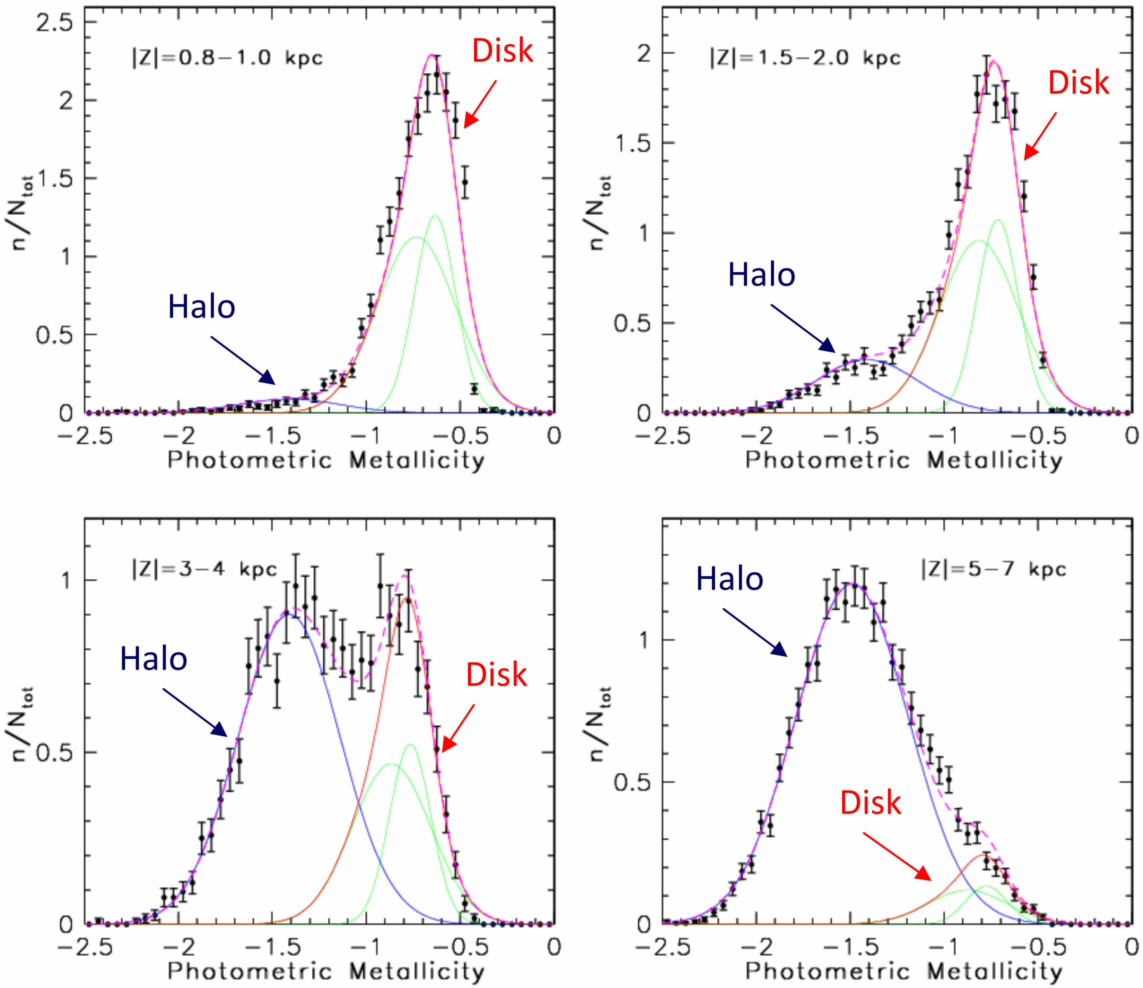
$$H_\mu = 1.0\text{kpc},\ \mu_\infty = -0.78,\ \Delta_\mu = 0.35$$

- Disk metallicity distribution:
  - Approximately fitted with a gaussian with Z-dependent mean, $\Phi([Fe/H]) \sim G(\mu_D, \sigma=0.16)$
  - Best fit by an asymmetric distribution with a slight low-metallicity tail

Asymmetric Disk MDF



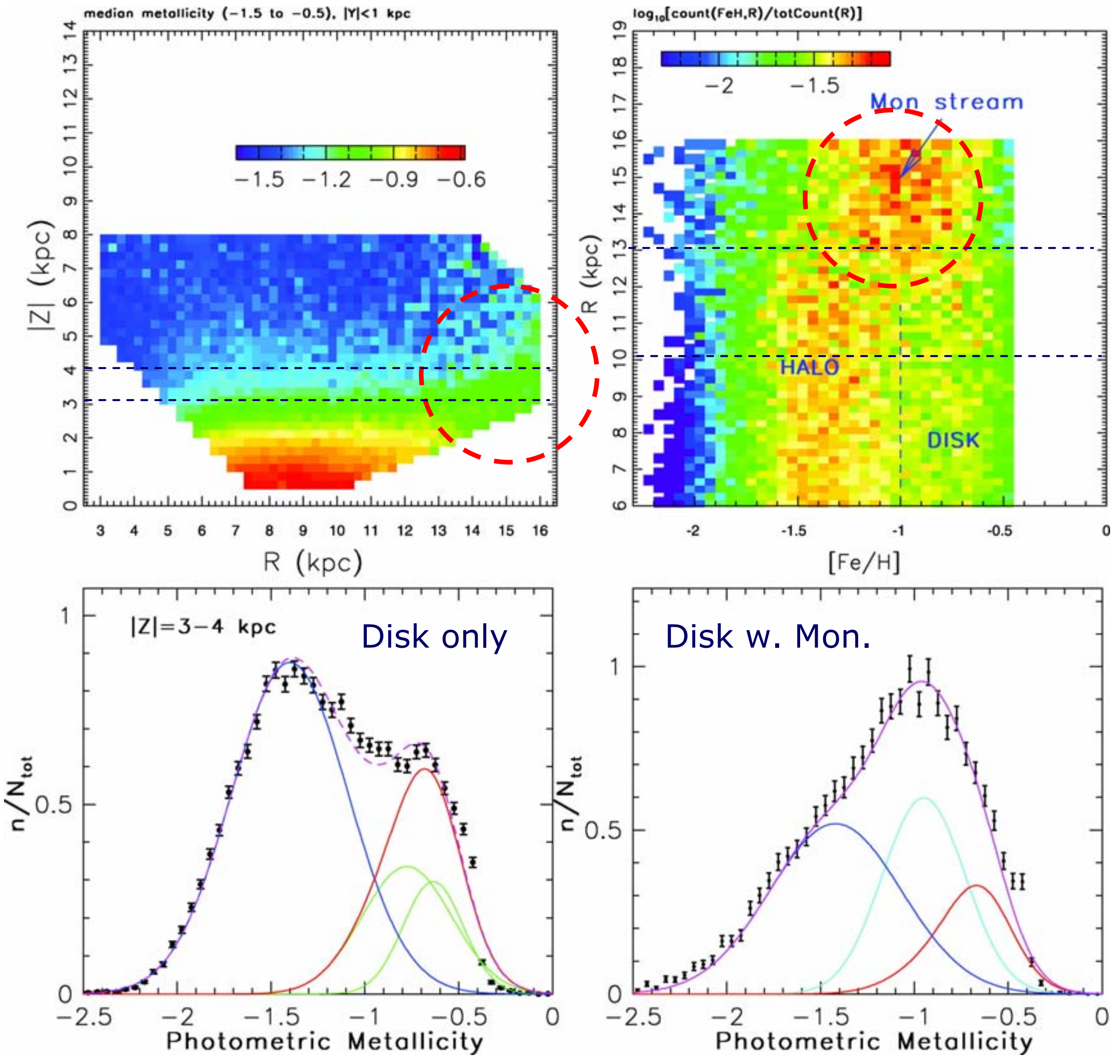




$$\Phi_{\text{disk}}([Fe/H]) \propto G(\mu_D, \sigma = 0.11) + 1.7 \times G(\mu_D - 0.1, \sigma = 0.21)$$

Monoceros Stream

Ivezic et al. (2008)



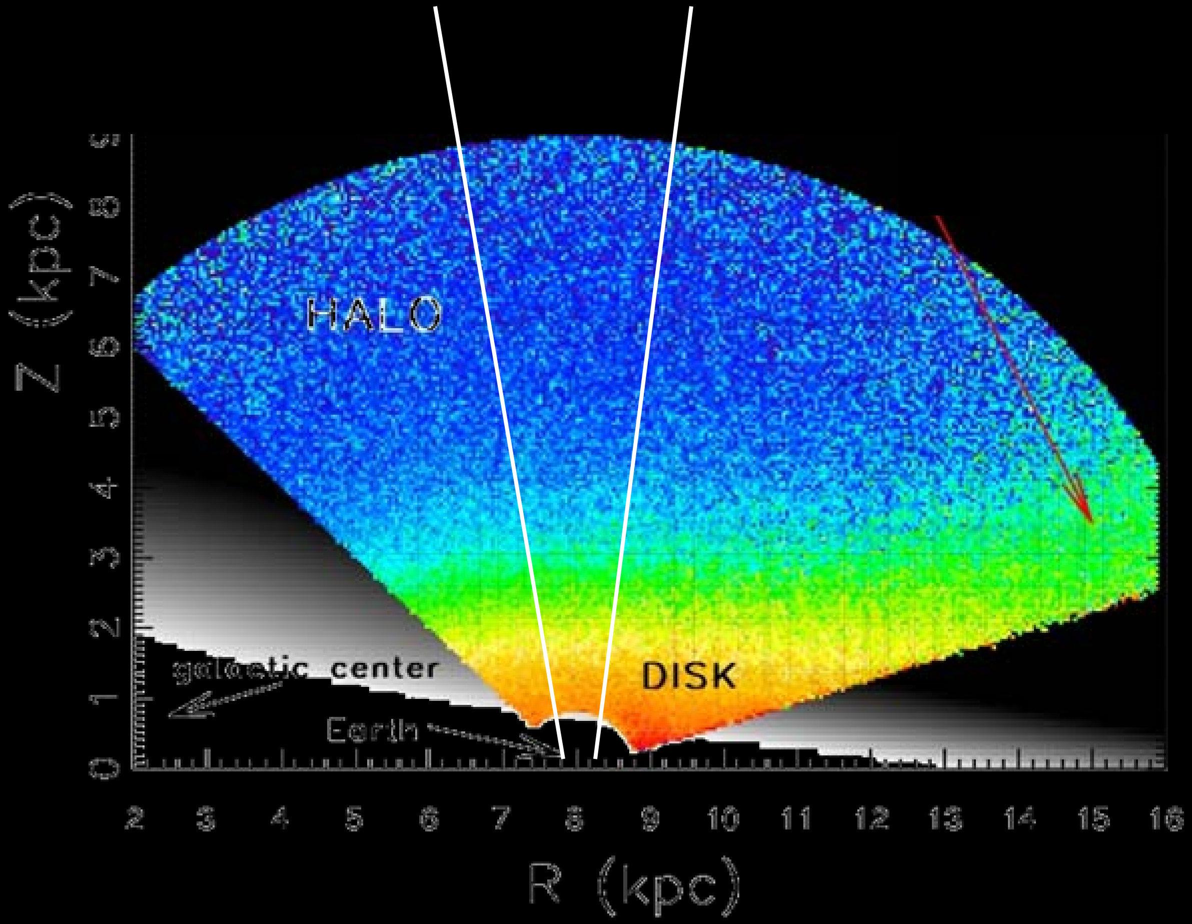
- Monoceros stream (Newberg et al. 2003) clearly distinct in metallicity space
- Metal poor compared to the disk, but metal rich compared to the halo ([Fe/H] = -0.95 dex)

- Strong evidence for external origin (merger remnant, as opposed to disk flaring or excitation)

Story so far

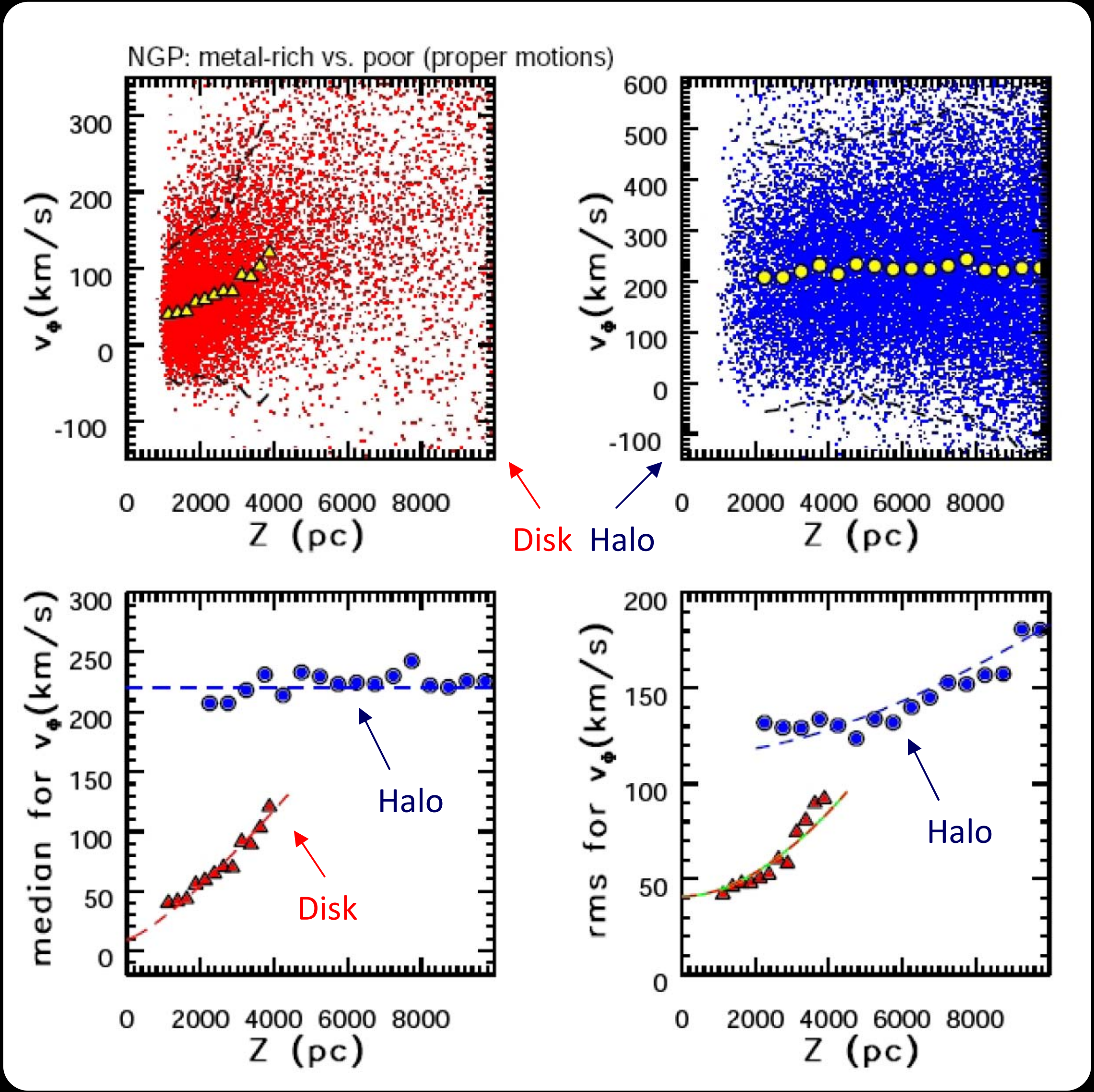
- Clear disk/halo dichotomy
- No radial metallicity gradient (within the observed volume)
- Vertical metallicity gradient in the disk
- Asymmetric disk MDF
- Distinct metallicity signature of Monoceros stream

Adding Kinematics: Proper motions towards the NGP



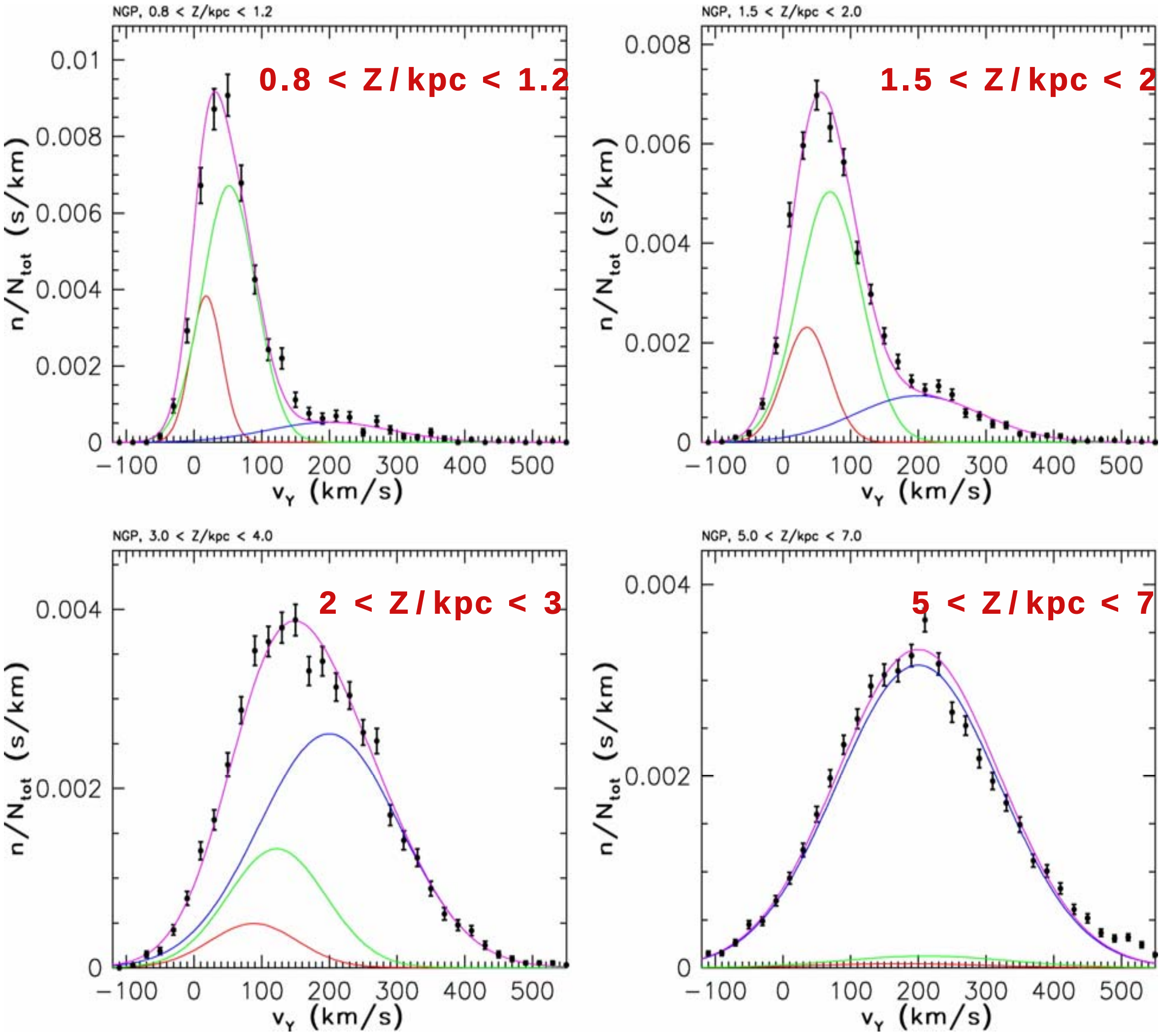
Easy to interpret: $v_{\phi} = \mu_b \times D$ is the rotational velocity

Halo/Disk Components, Disk Rotational Velocity Lag



- Top panels: small dots are individual stars, large symbols are the median values
- Top left: disk stars show clear rotational velocity lag
- Top right: halo stars $v_\phi \sim 220$ km/s, no significant rotation
- Bottom left: disk velocity lag not linear
- Bottom right: halo velocity dispersion increase consistent with being due to photometric errors only

Rotational velocity distribution functions



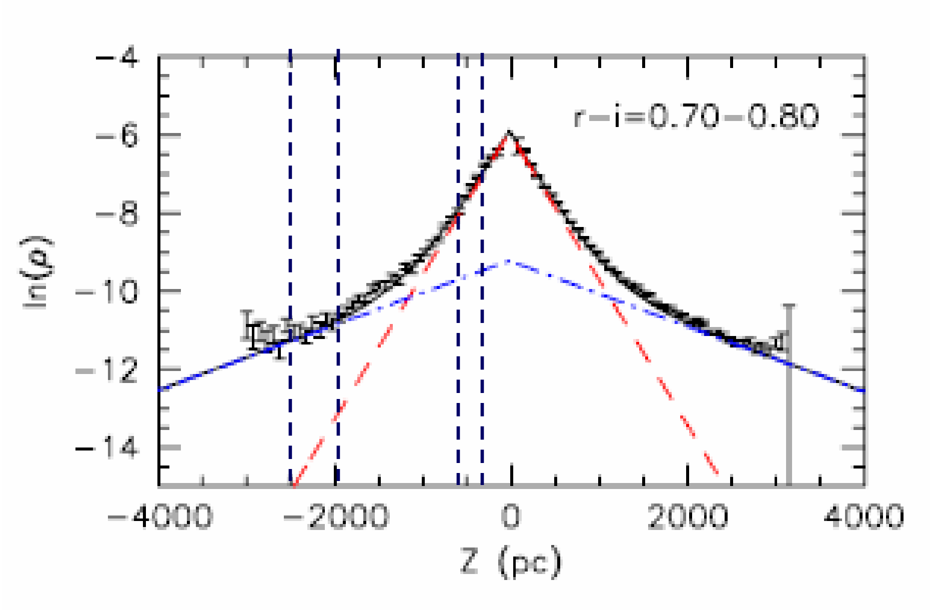
1. Disk: Asymmetric rotational velocity distribution with Z-gradient

2. Halo: Unimodal, Gaussian velocity distribution of fixed dispersion and mean

Revisiting the Thin/Thick Disk Dichotomy

- Vertical density distribution exhibits a break
- Metallicity distribution exhibits a metal-weak tail
- Rotational velocity distribution exhibits a lower-velocity tail

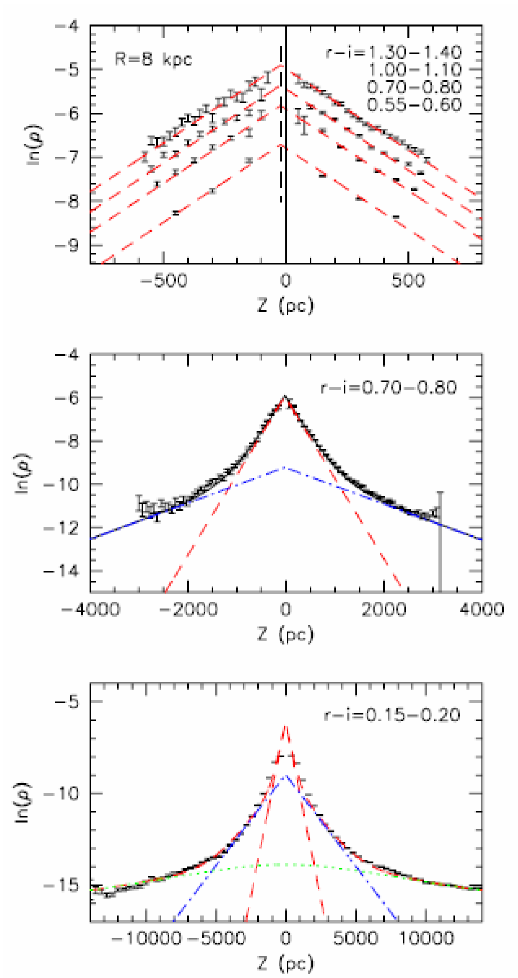
- Is there evidence for a model of the density, metallicity, and velocity distributions as a superposition of two distinct populations?
  - Metal-rich, kinematically cold, thin disk
  - Metal-poor, kinematically warm, thick disk?

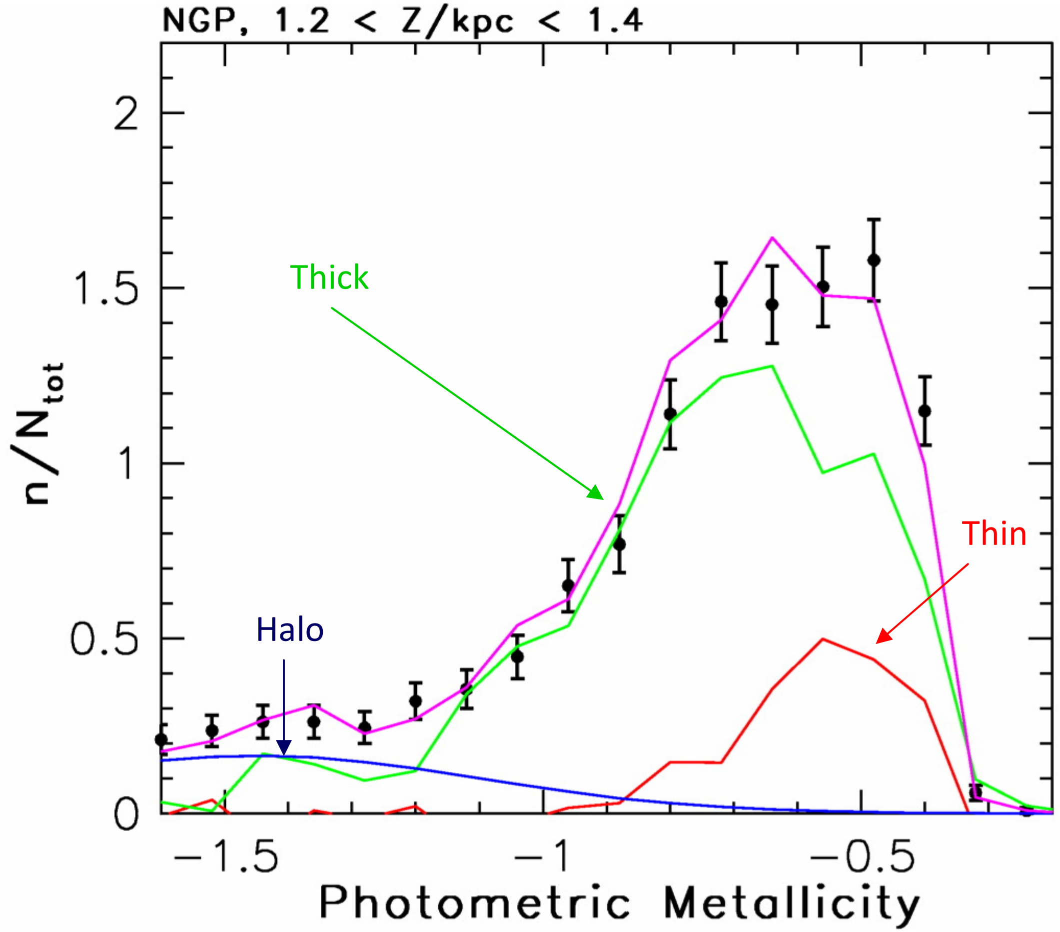


Assumption / Definition: The exponentials in the density profile can be identified with the thin / thick disk component

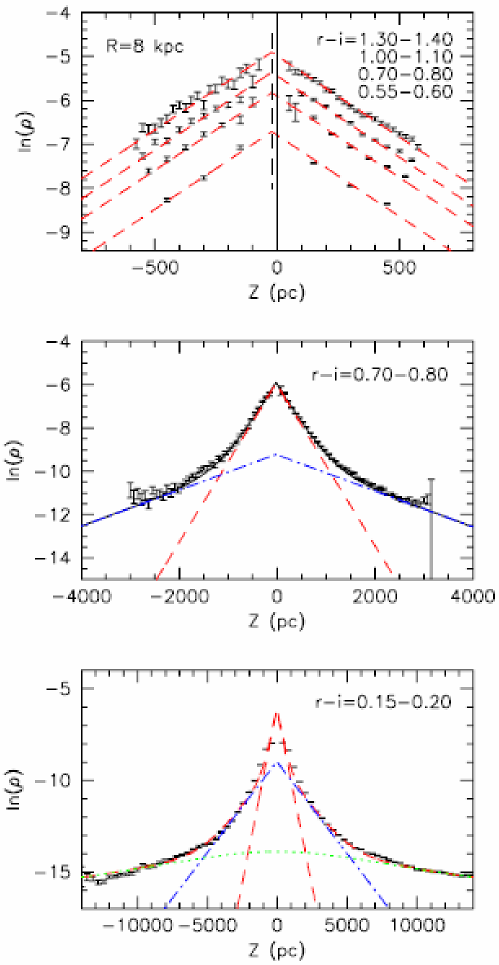
=> Can directly extract thin / thick disk MDFs

Empirical Metallicity Distribution Function





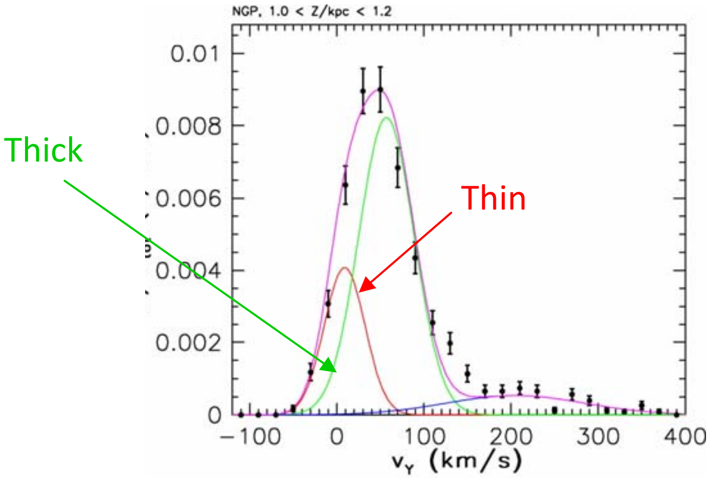
Rotational Velocity Distributions

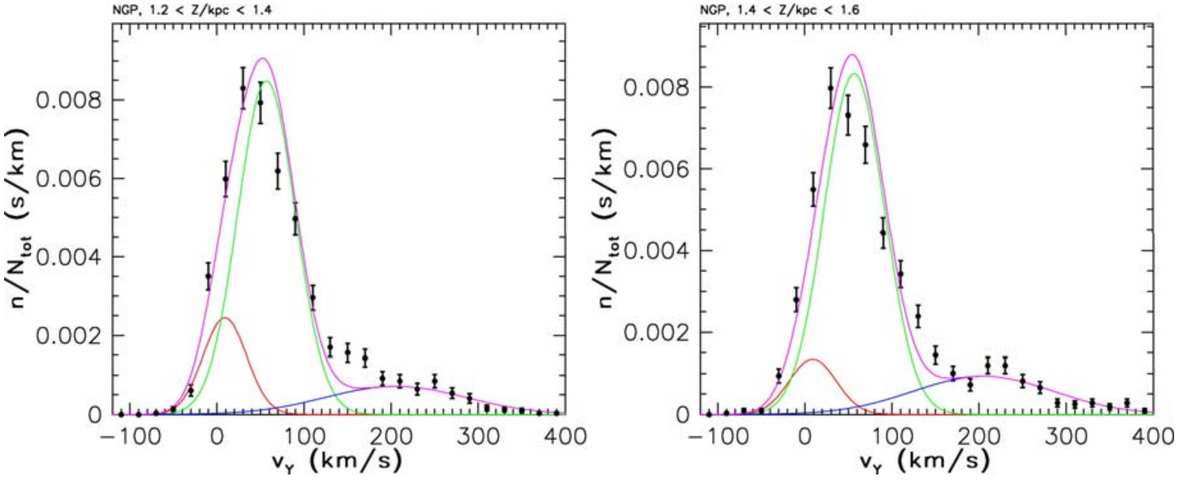


Rotational velocity distributions at various Z

v0_thin = 9 km/s

v0_thick = 57 km/s

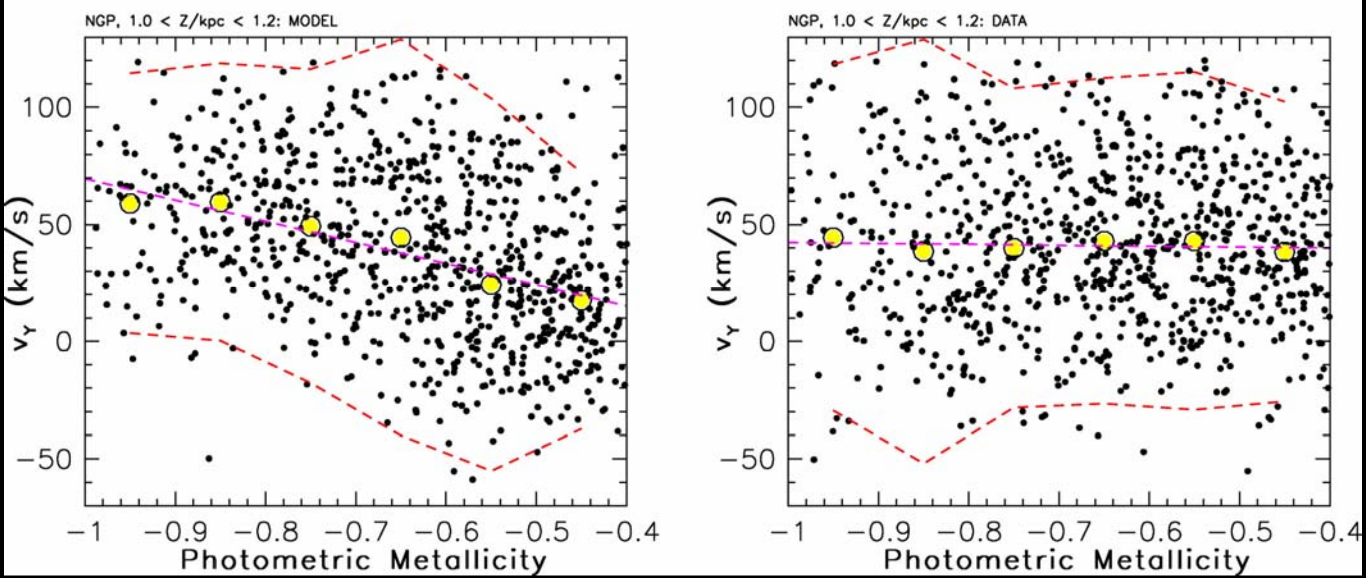




Approximation: d(vrot) / dZ = 0 !

Metallicity-rotational Velocity Correlation

Ivezic et al. (2008)

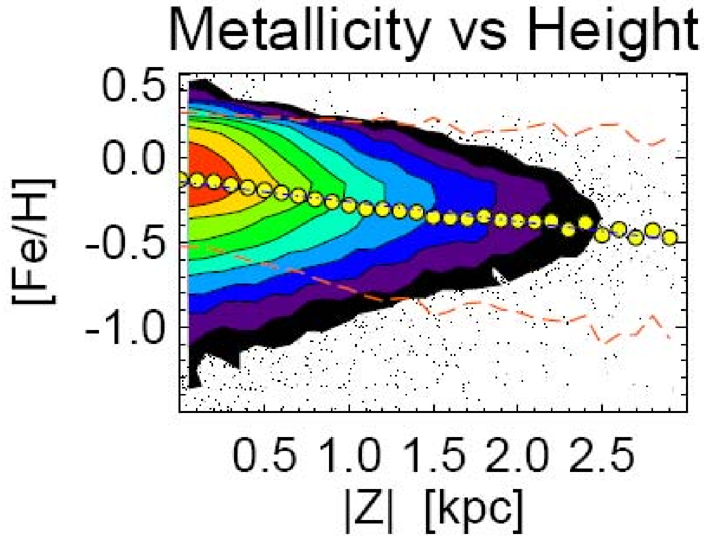


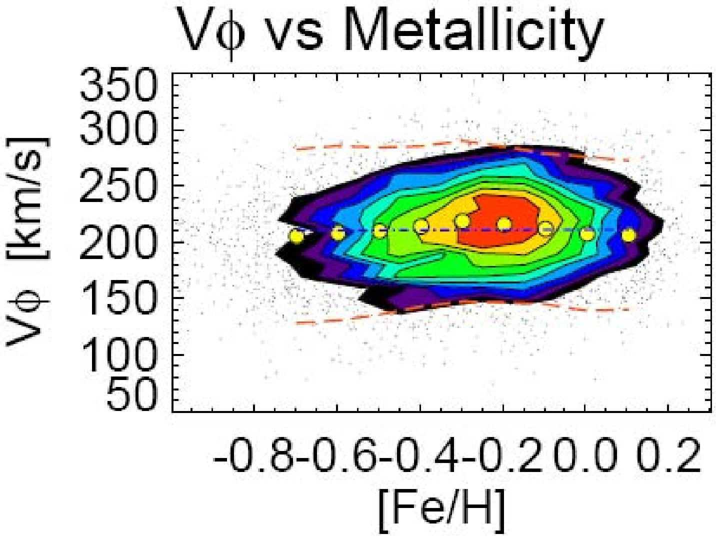
- Left: Expected rotational velocity-metallicity correlation at 1kpc < Z < 1.2kpc
- Right: Observed metallicity-rotational velocity correlation

Comparison with simulations

Figures and analysis by Sarah Loebman (UW), simulation by Rok Roškar.

Loebman et al. (in prep).





Thick disk formation: Sudden, in situ or accreted?

- We find no evidence for the thick disk being a clearly distinct component
  - Poses a potential problem for formation of the thick disk via a sudden, single, large, accretion event
  - Gradual heating of the disk by many mergers cannot be excluded
  - Caveat: Model admittedly simple. Will be revisited in the context of dynamical models of the Galaxy (work in progress)

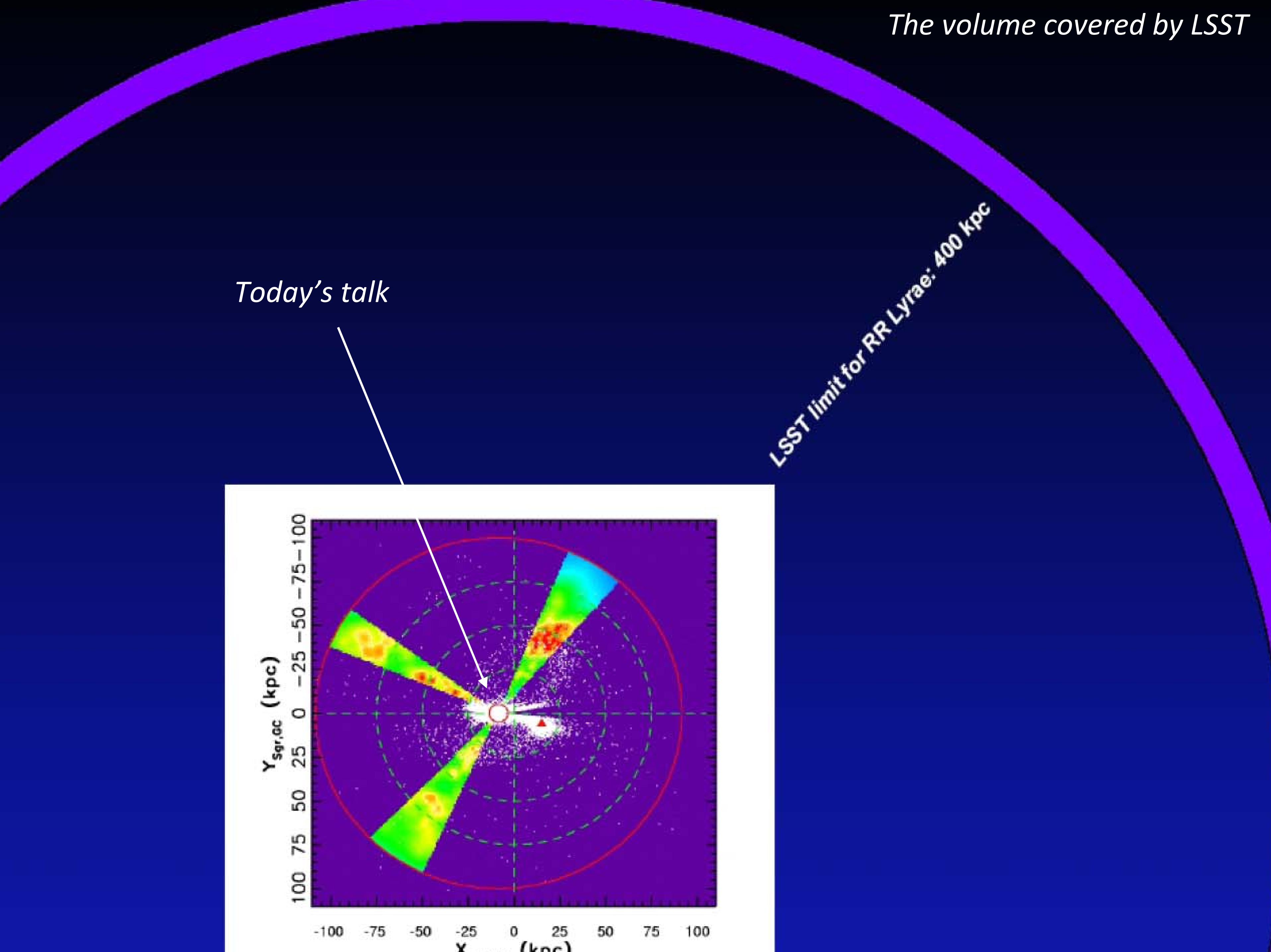
- Abundance dichotomy
  - Usually used to argue for “catastrophic” thin/thick disk formation
  - Not so: see Schonrich & Binney (arXiv: 0809.3006v1)

- Observations consistent with in-situ formation
  - Vertical metallicity gradients, *[Fe/H]* vs. $v\phi$ correlation and radial metallicity gradient
  - Radial migration is **important**

Applications to Future Surveys

- Methods directly applicable to current and planned surveys
- SkyMapper
  - “SDSS south”, deeper, faster, better
  - u, v_S, g, r, i bands
- Pan-STARRS
  - ~2.5 mag deeper than SDSS
  - gri bands
- LSST

The volume covered by LSST

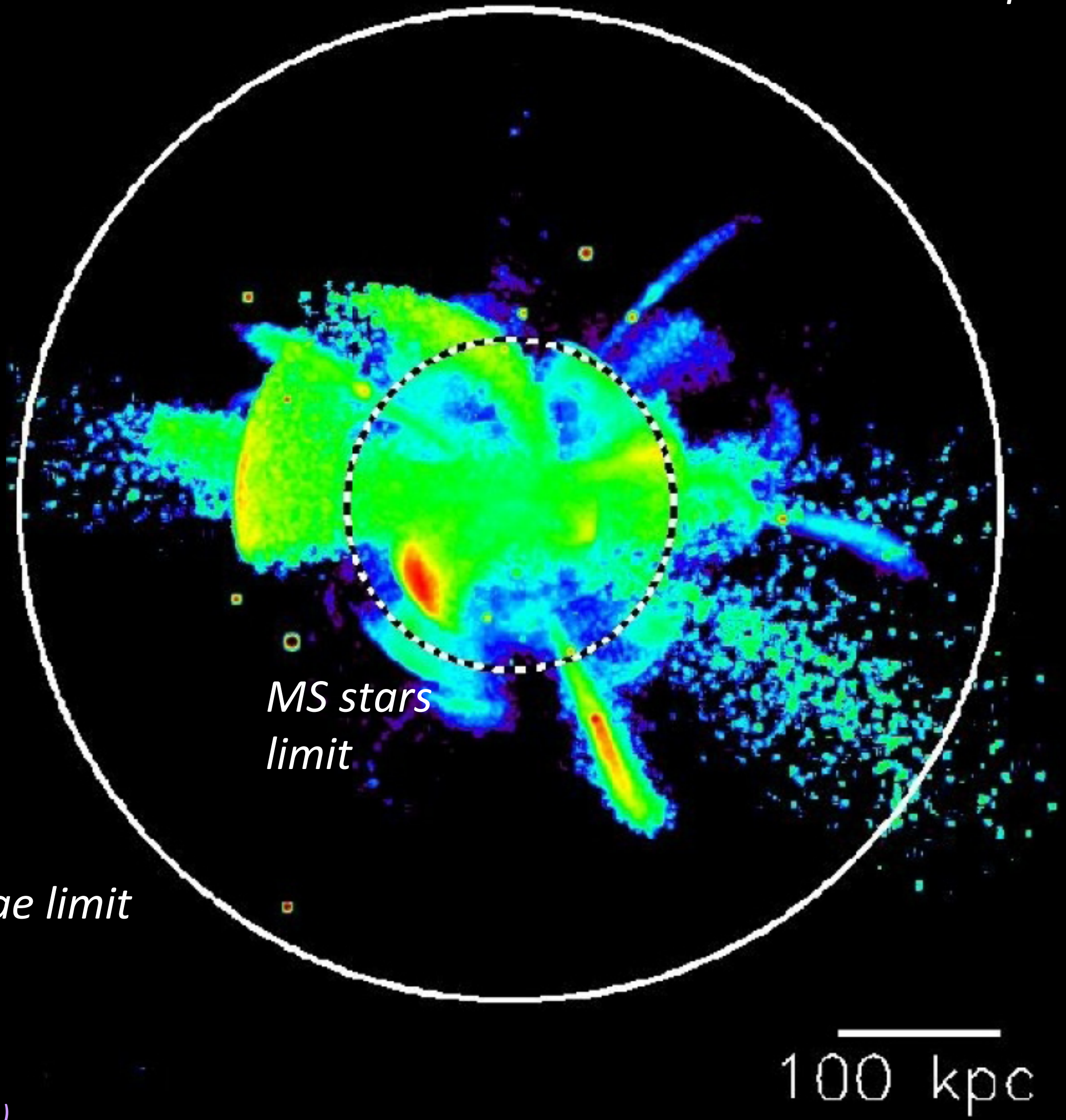


Today's talk

LSST limit for RR Lyrae: 400 kpc

The Local Group Tomography With LSST

The expected substructure.

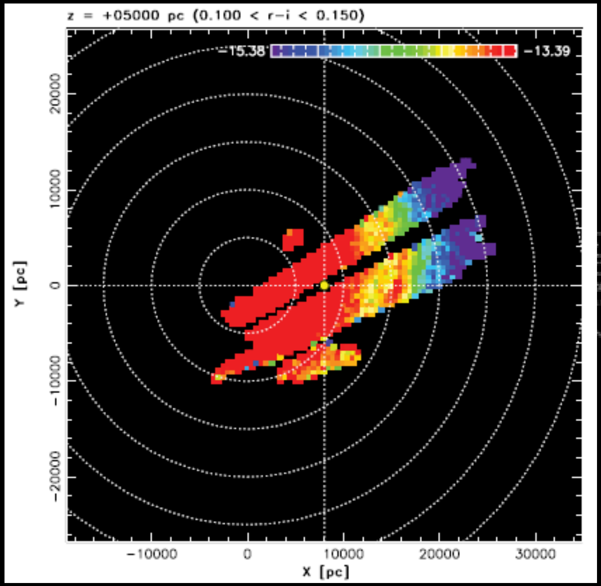


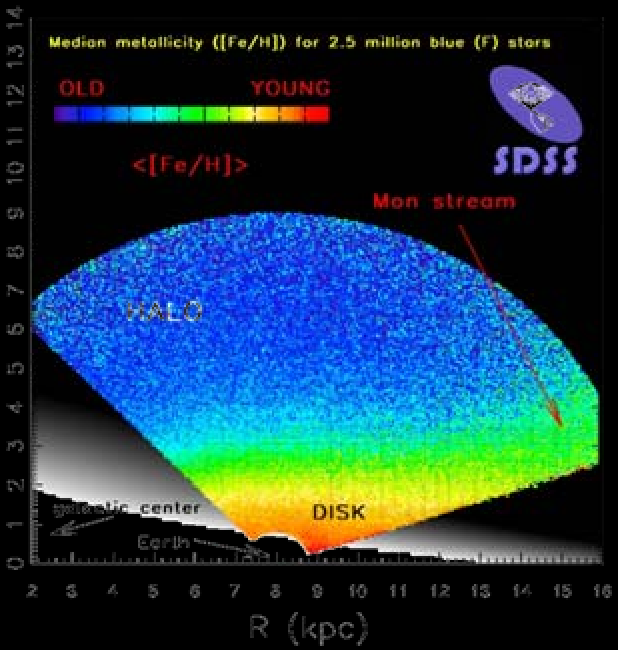
MS stars limit

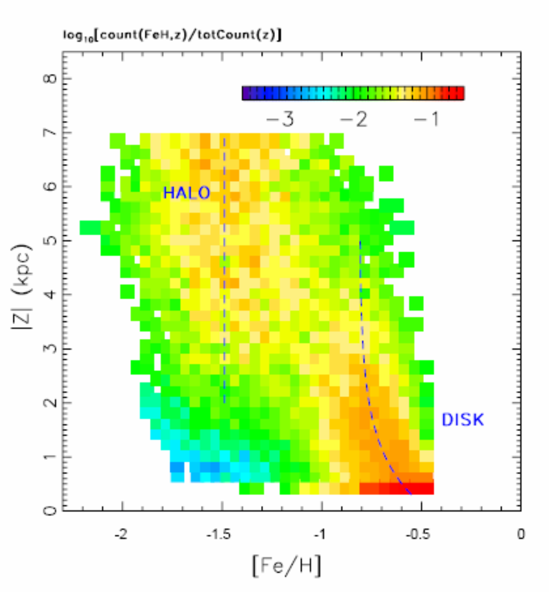
RR Lyrae limit

Bullock & Jonhston (2005)

Mapping the Milky Way with SDSS :: Strategy







1. Directly measure the distribution $\Phi(\vec{r}, \vec{v}, [Fe/H])$ of stellar number density, kinematics, and metallicity in a representative volume of the Galaxy.

2. **Use these distributions to learn about [Gg]alaxy formation, evolution, interactions with environment, and the distribution of mass.**

Summary

- Measurements of density/metallicity/velocity distribution with 2 orders of magnitude larger samples than pre-SDSS studies (e.g., in ~10% of Galactic disk volume)
  - Mostly ahead of theory
  - Setting a goal for modelers for the years to come

- Clumps/streams are an integral part of Milky Way structure, both halo and the disk.

- Clear separation of disk and halo metallicity distributions, asymmetric disk dist.

- Problems with thin/thick disk separation
  - Thin/thick disk separation based on metallicity is inconsistent with separation based on density laws
  - Separation based on kinematics is inconsistent with separation on both metallicity and density laws
  - Metallicity and kinematics largely uncorrelated

- Methods and codes directly applicable to future wide-field surveys (SkyMapper+RAVE, PanSTARRS, DES, LSST)

“The Milky Way Tomography with SDSS. I. Stellar Number Density Distribution”, Juric et al., 2008, ApJ, 673, 864

“The Milky Way Tomography with SDSS. II. Stellar Metallicity”, Ivezic et al., ApJ, in press (arXiv:0804.3850)

“Candidate Wide Binaries in the Sloan Digital Sky Survey”, Sesar et al., ApJ, in press

“The Milky Way Tomography with SDSS. III. Stellar Kinematics”, Bond et al., in prep.

“The Luminosity Function of Galactic Disk and Halo”, Juric et al., in prep.