Global Views of the Stellar Distribution and Kinematics in the Milky Way

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I worked 7 years for Robert Lupton – what doesn't kill you makes you stronger :) [I do (often) miss him, really!]

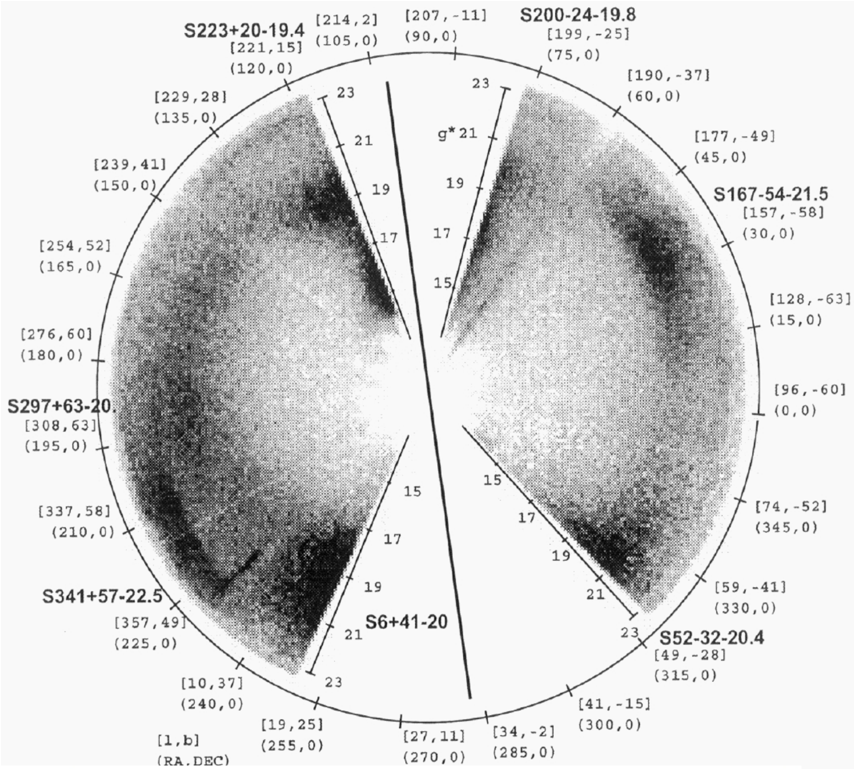
Outline

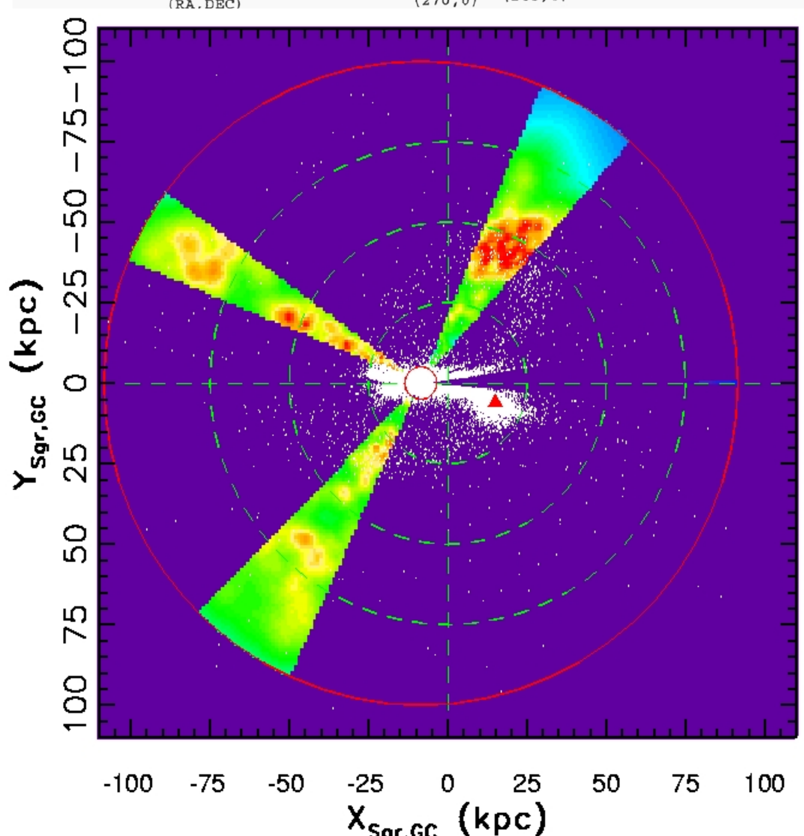
1. 3D (6D) description of the Galaxy's spatial distribution of stars (and their kinematics)

2. Photometric Parallax Method

3. The spatial distribution of stars in the Galaxy

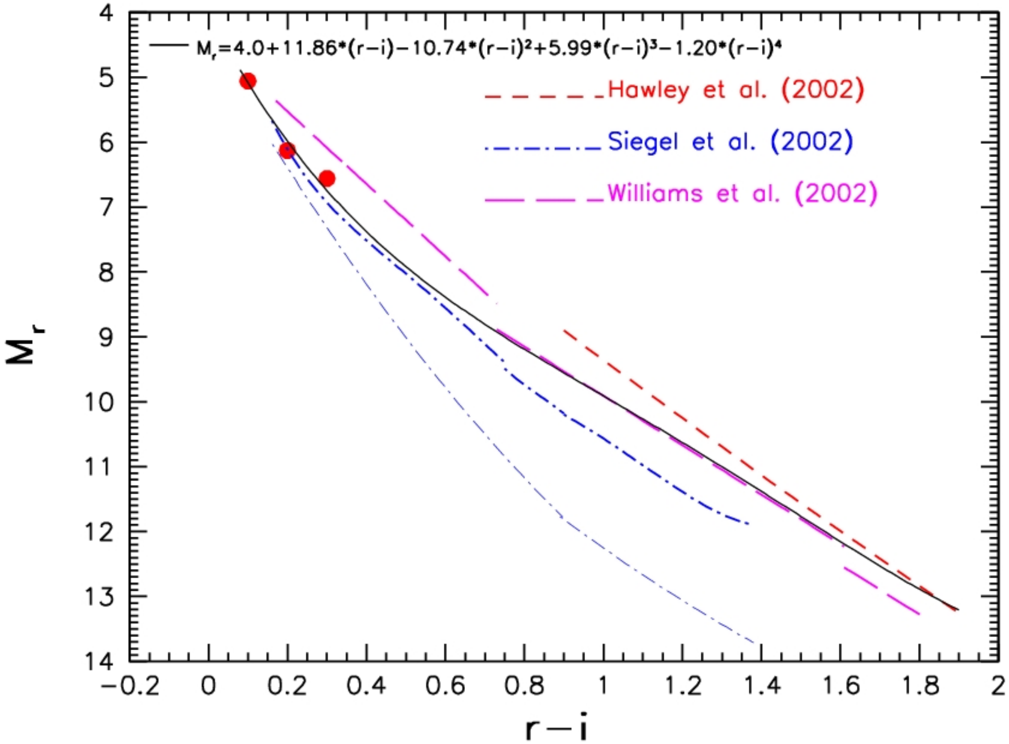
4. The Milky Way Kinematics

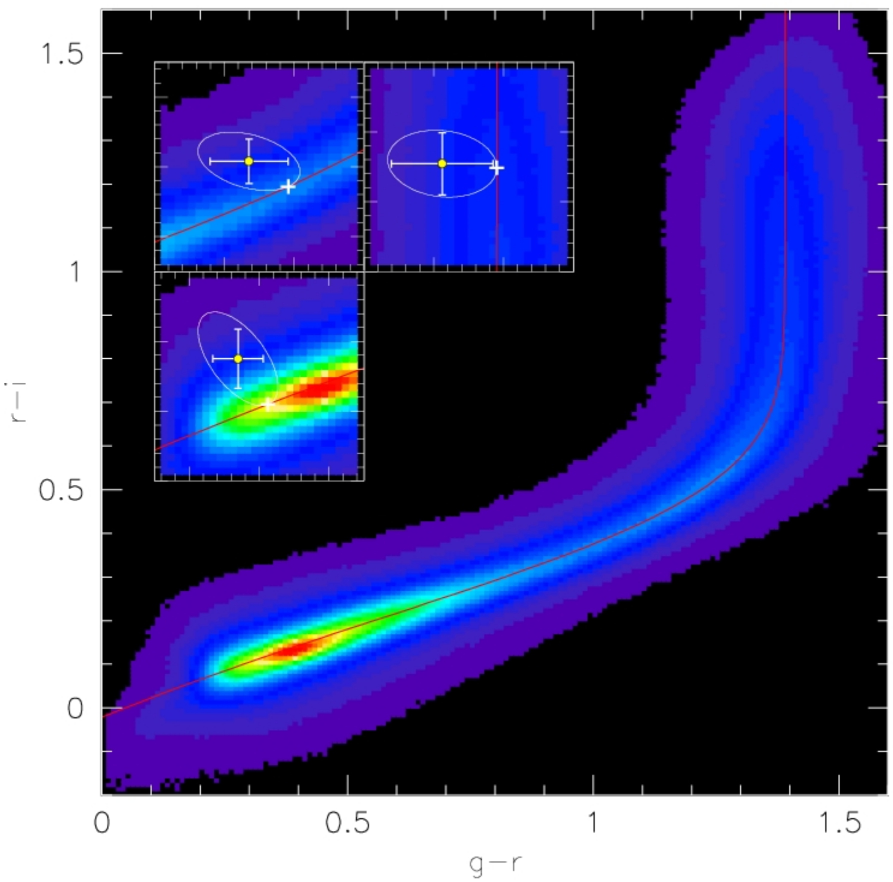




The Milky Way Maps

- Top left: F stars from Newberg, Yanny et al. (2002)
- Bottom left: RR Lyrae from Ivezić et al. (2003)
- How do we study and represent the full 3D structure, instead of selecting "special" planes as in these two examples?
- SDSS has obtained excellent photometric data for ∼ 100 million stars. How can one utilize these data for studying the disk component(s) (and not only outer halo)?
- What can we learn about kinematics using SDSS-POSS proper motions and SDSS radial velocities?





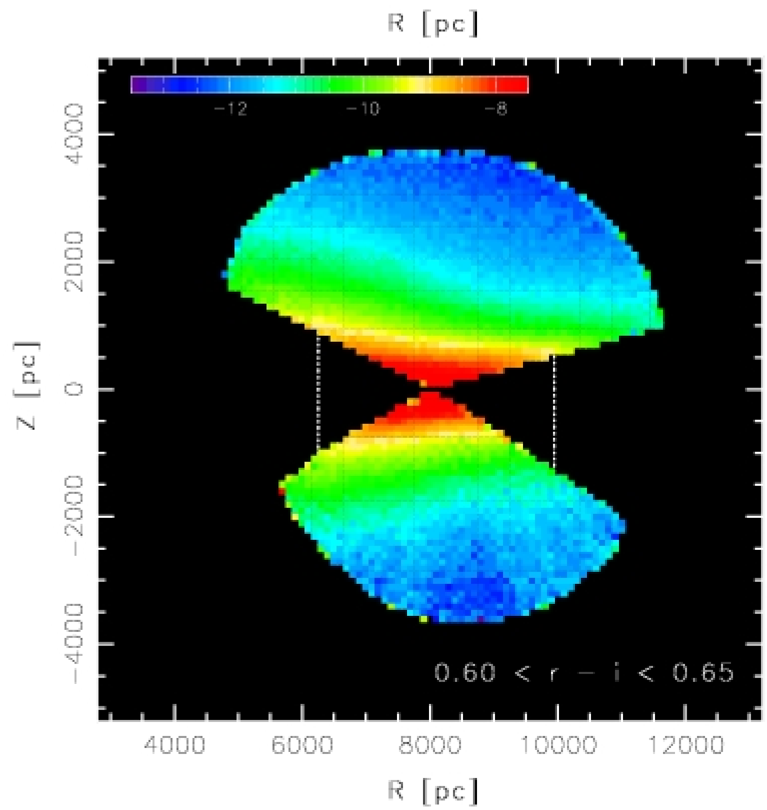
Photometric Parallax Method

- Adopted a single relation that agrees with geometric parallax measurements for nearby M dwarfs, and with globular cluster CMDs.
- To increase signal-to-noise at the faint end, stars are ML projected on the stellar locus
- Applied to 50 million stars in 6500 deg^2 and 100 pc to 15 kpc distance range
- Pitfalls: systematic errors in adopted relation (e.g. metallicity effects), contamination by giants, smaller distance range than for e.g. red giants and RR Lyrae

Dissecting Milky Way with SDSS

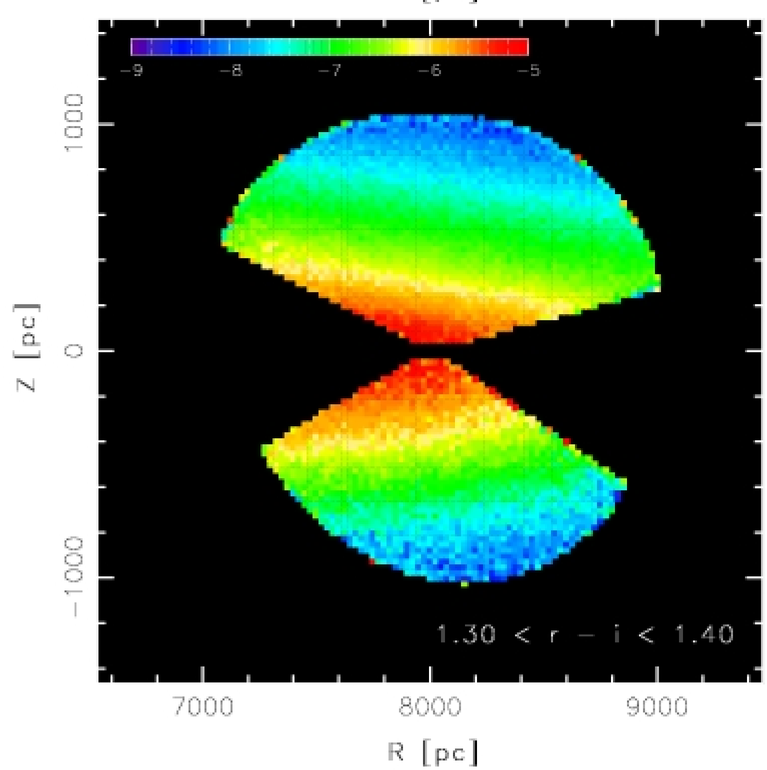
- Traditional approach: assume initial mass function, fold with models for stellar evolution; assume mass-luminosity relation; assume some parametrization for the number density distribution; vary (numerous) free parameters until the observed and model counts agree. Uniqueness? Validity of all assumptions?

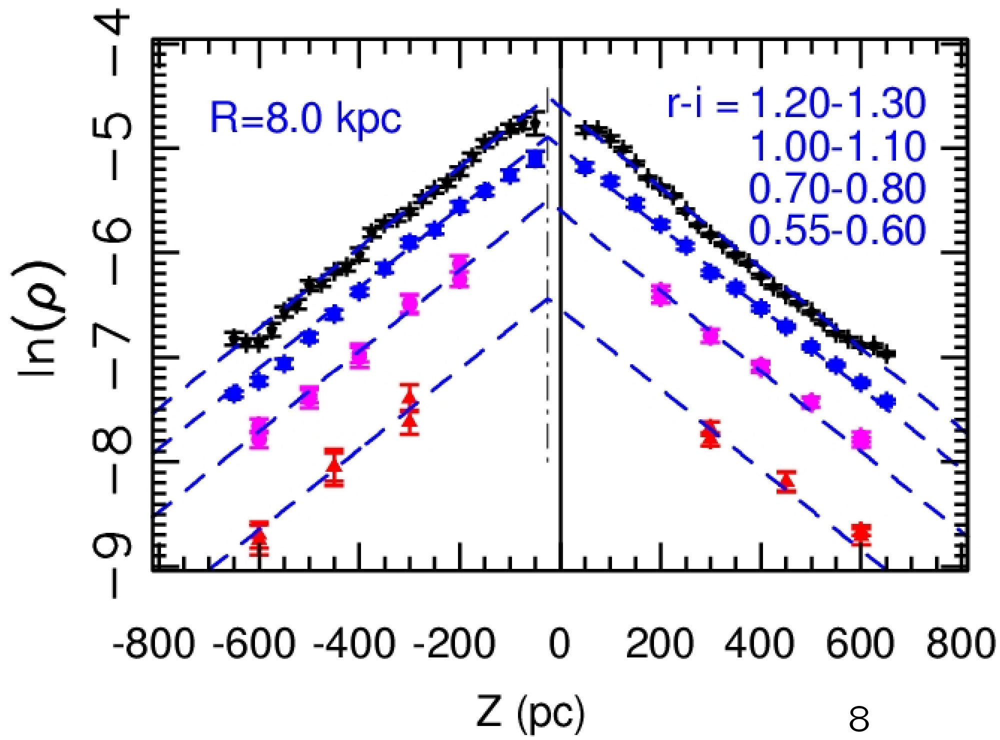
- SDSS photometric parallax approach: adopt color-luminosity relation, estimate distance to each star, bin the stars in XYZ space and directly compute the stellar number density (for each narrow color bin). There is no need to a priori assume, the number of, and analytic form for Galactic components



Local maps: thin disk

- Red(ish) stars have small luminosity: sampled to a few kpc
- The maps are roughly consistent with an exponential disk out to ∼1 kpc: 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

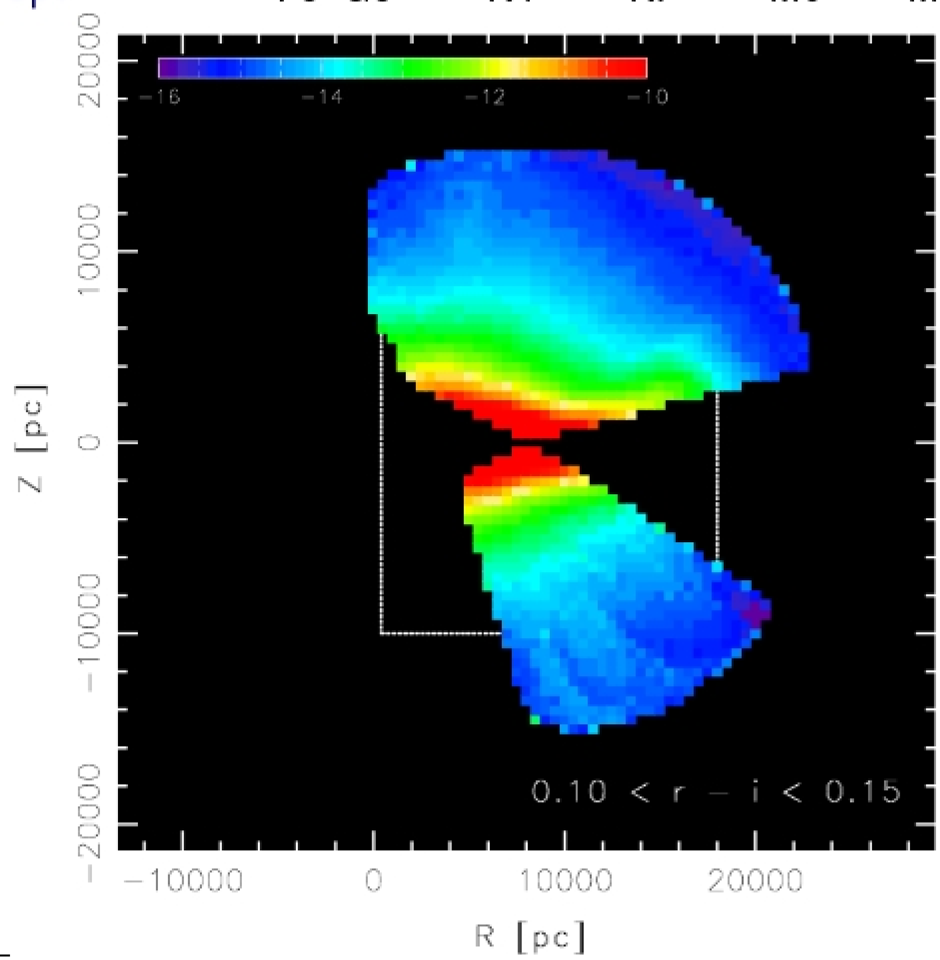


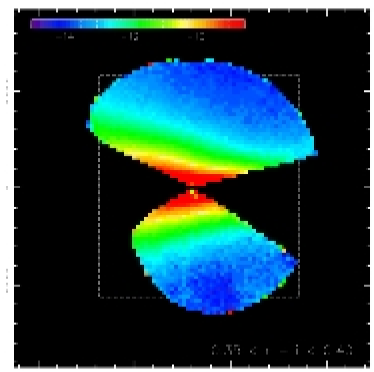


The r-i color bins sample a variety of scales

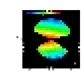
19 r–i color bins – 19 density maps

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

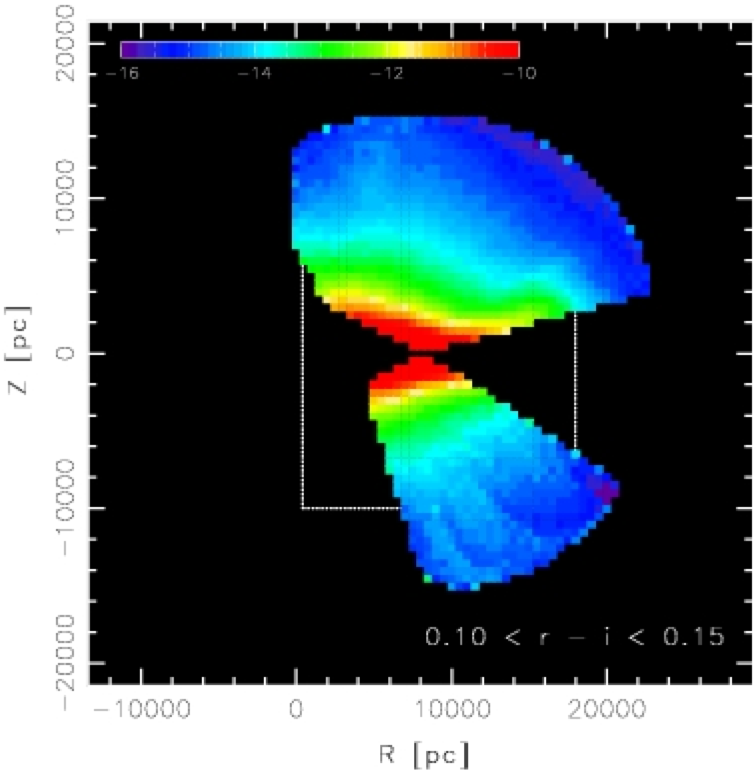


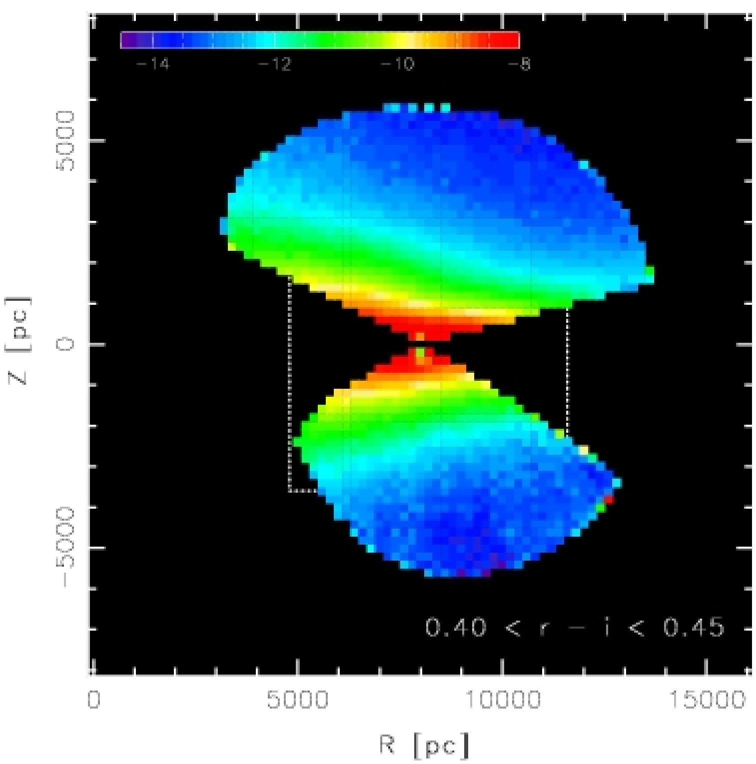


0.35 < r-i < 0.40



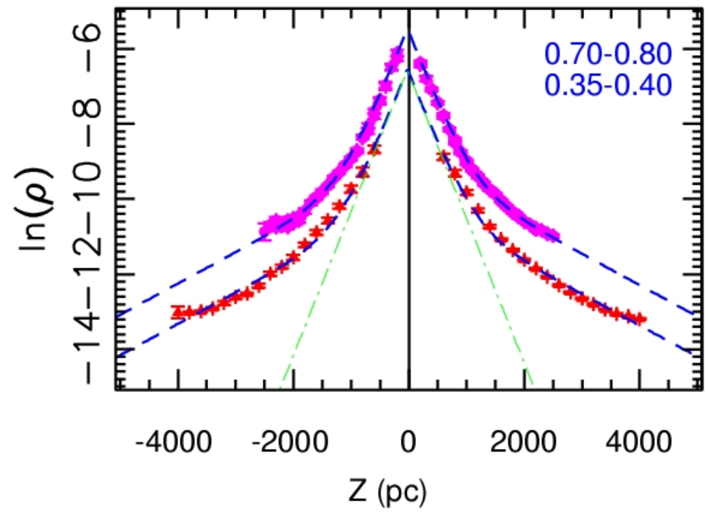
1.3 < r-i < 1.4

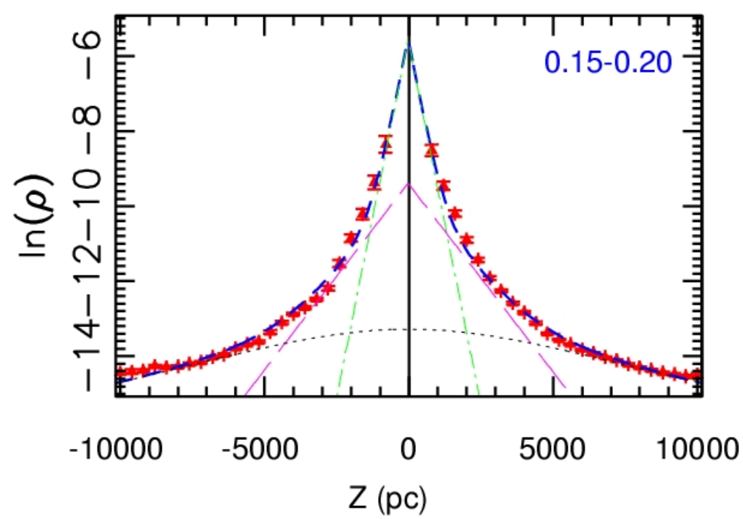


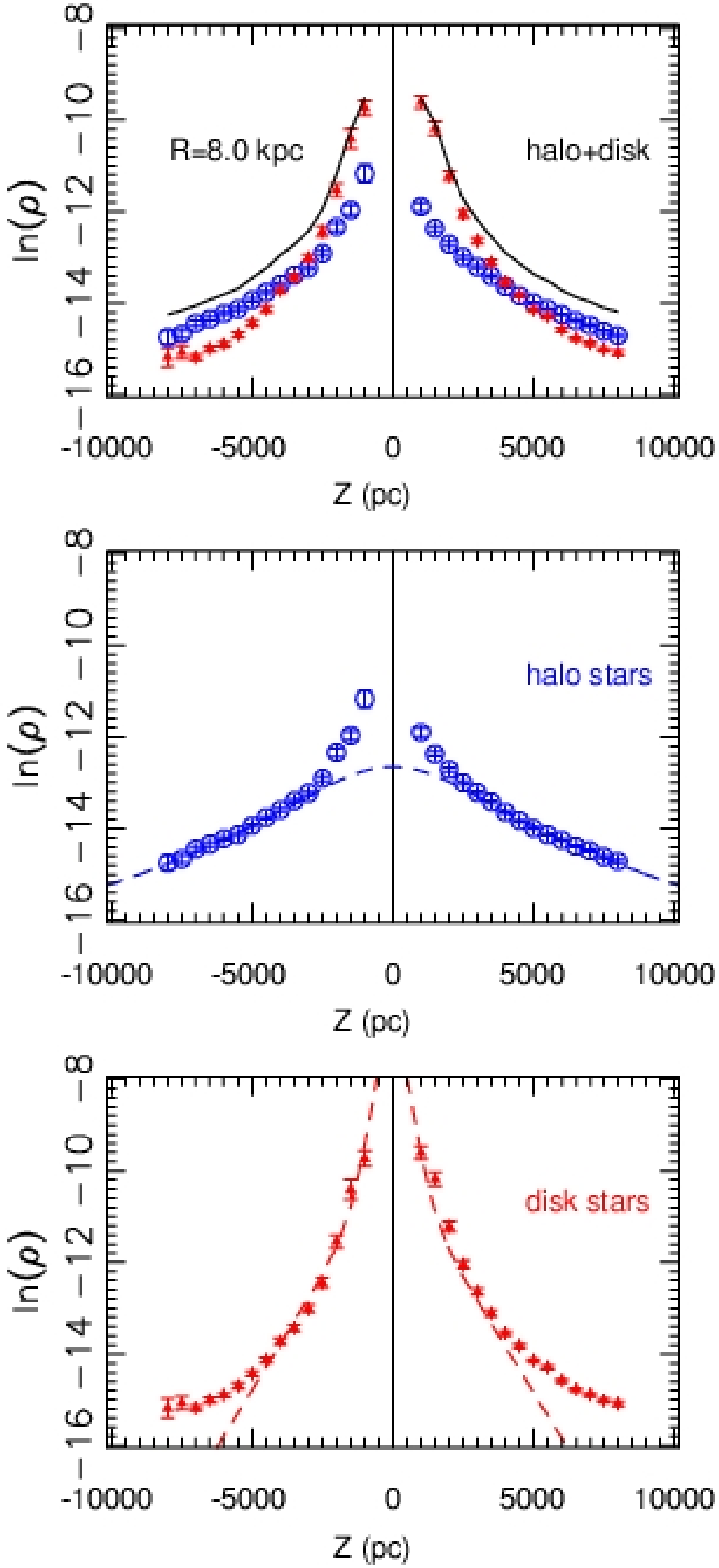


Thin to thick disk transition

- Yellow(ish) stars have intermediate luminosities: sample the transition from thin to thick disk at a few kpc







Is the Thick Disk Really Needed?

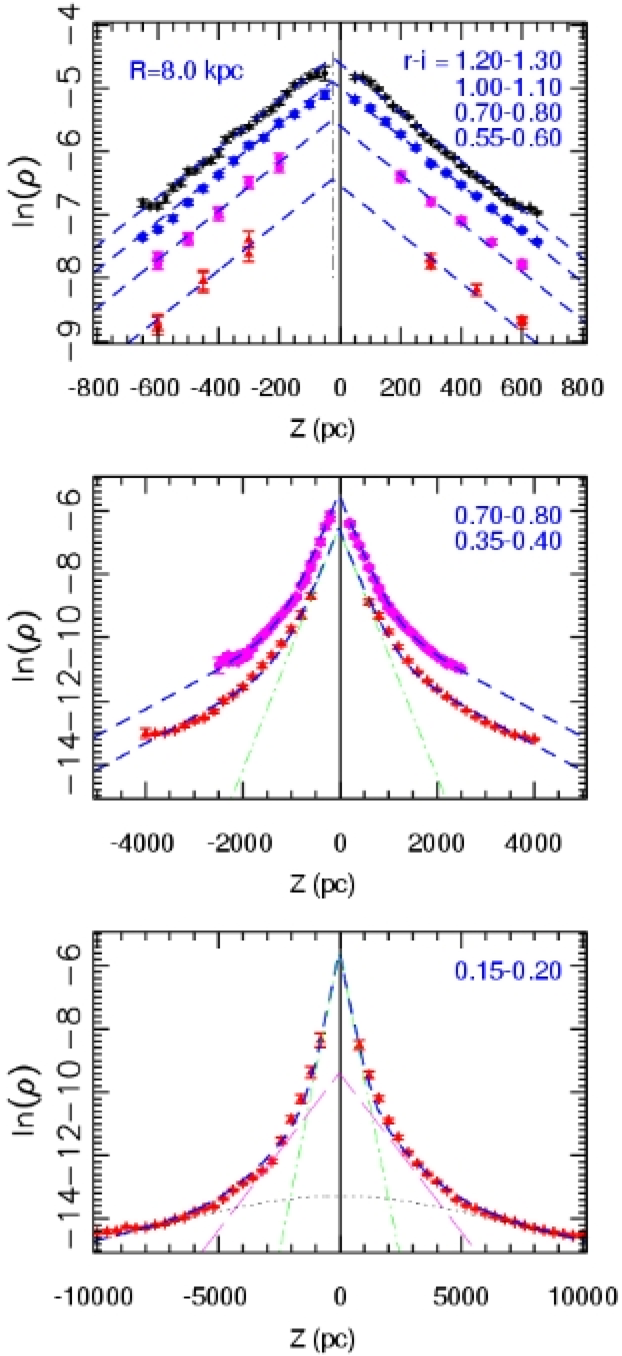
- It is not needed to fit $\rho(Z|R = R_\odot$: an appropriate halo, with a thin disk, can explain the counts
- However, when stars are separated by metallicity (using $u-g$ color as a proxy), low-metalicity stars follow the halo component, and the density profile for high-metalicity stars requires the thick disk component (or, at least, a profile different from a single exponential disk)
- A more robust estimate of the required number of components could be obtained by the full 2D analysis of the density maps, but. . .

Modeling the smooth component

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

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

- Sech^2 models for disks
- Miyamoto & Nagai (1975) profile



R=8 kpc cross-sections and model predictions

Best fit parameters

$$Z_0 = 24\,pc \pm 5\,pc$$

$$h_{thin} = 270 \pm 10\,pc$$

$$l_{thin} = 2400 \pm 200\,pc$$

$$h_{thick} = 1400 \pm 50\,pc$$

$$l_{thick} = 3500 \pm 500\,pc$$

$$\rho_{thick} / \rho_{thin} = 0.06 \pm 0.01$$

$$\rho_{halo} / \rho_{thin} \sim 0.0001$$

$$q \cong 2$$

$$n \sim 1-3$$

Model fit residuals

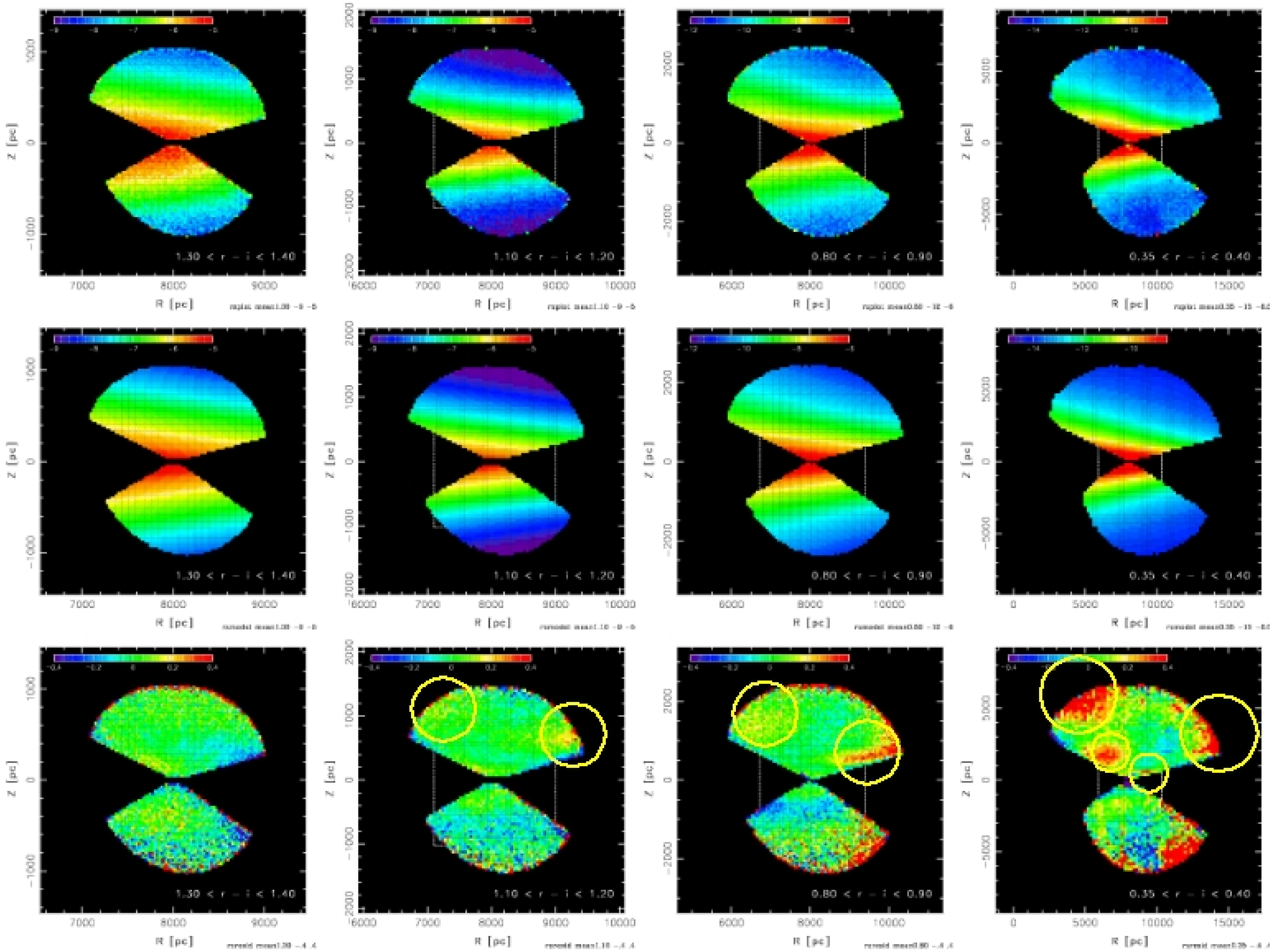
Scale increases this way

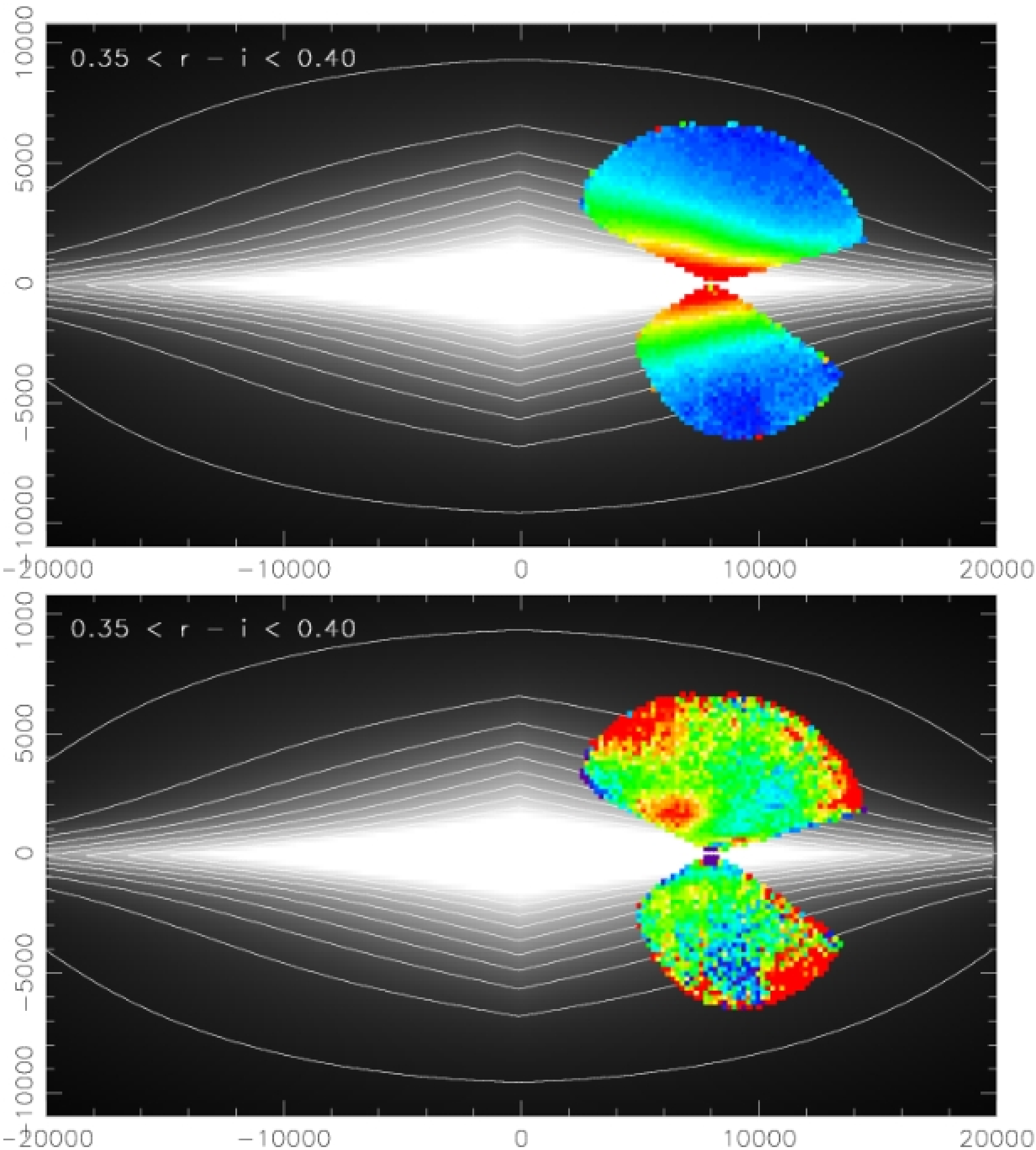
1.3 < r-i < 1.4 | 1.1 < r-i < 1.2 | 0.8 < r-i < 0.9 | 0.35 < r-i < 0.40

Data

Model

D/M-1





The Milky Way

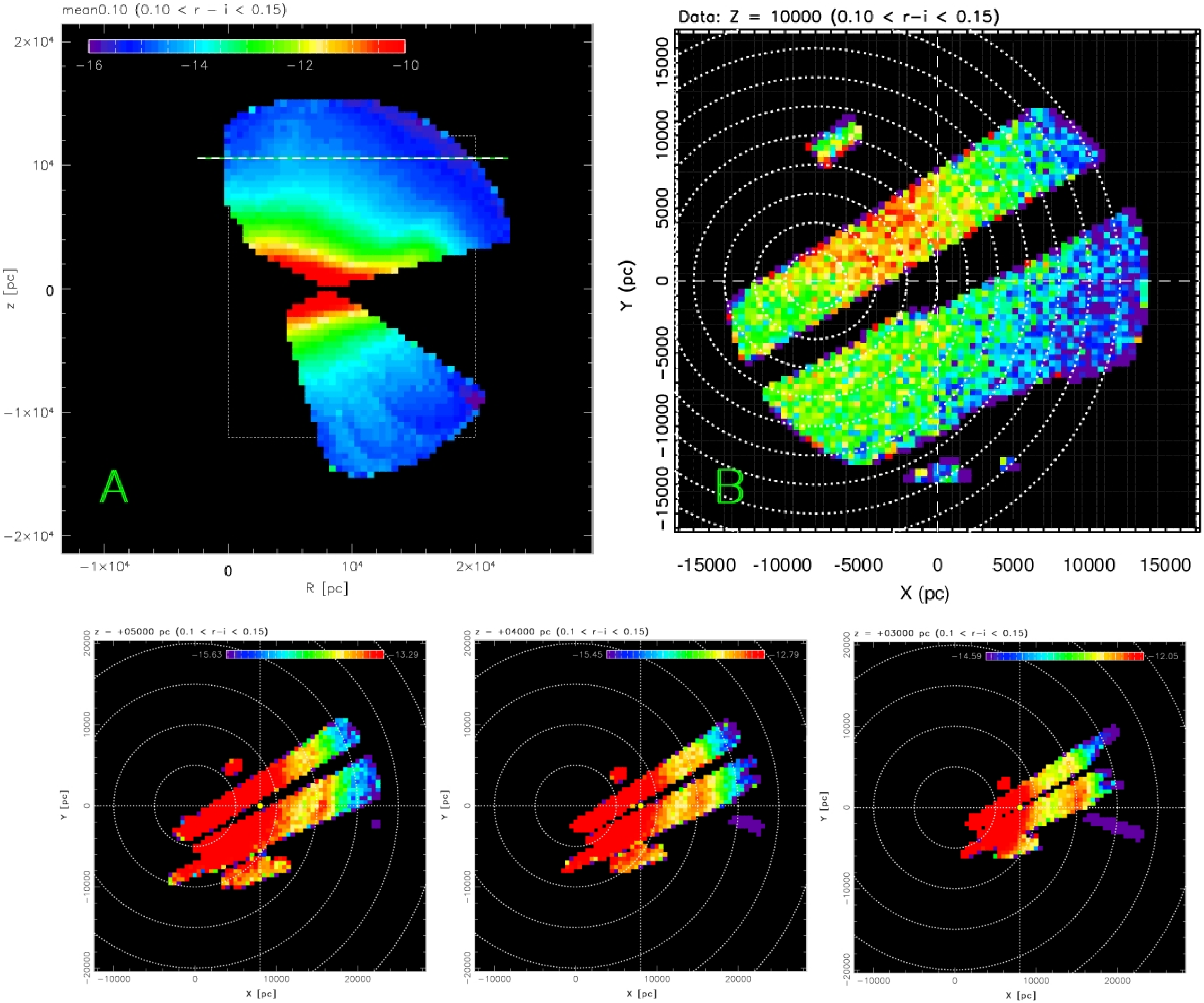
- 2 exponential disks

+ 1 oblate halo

+ Numerous clumps, both in the disk and the halo!

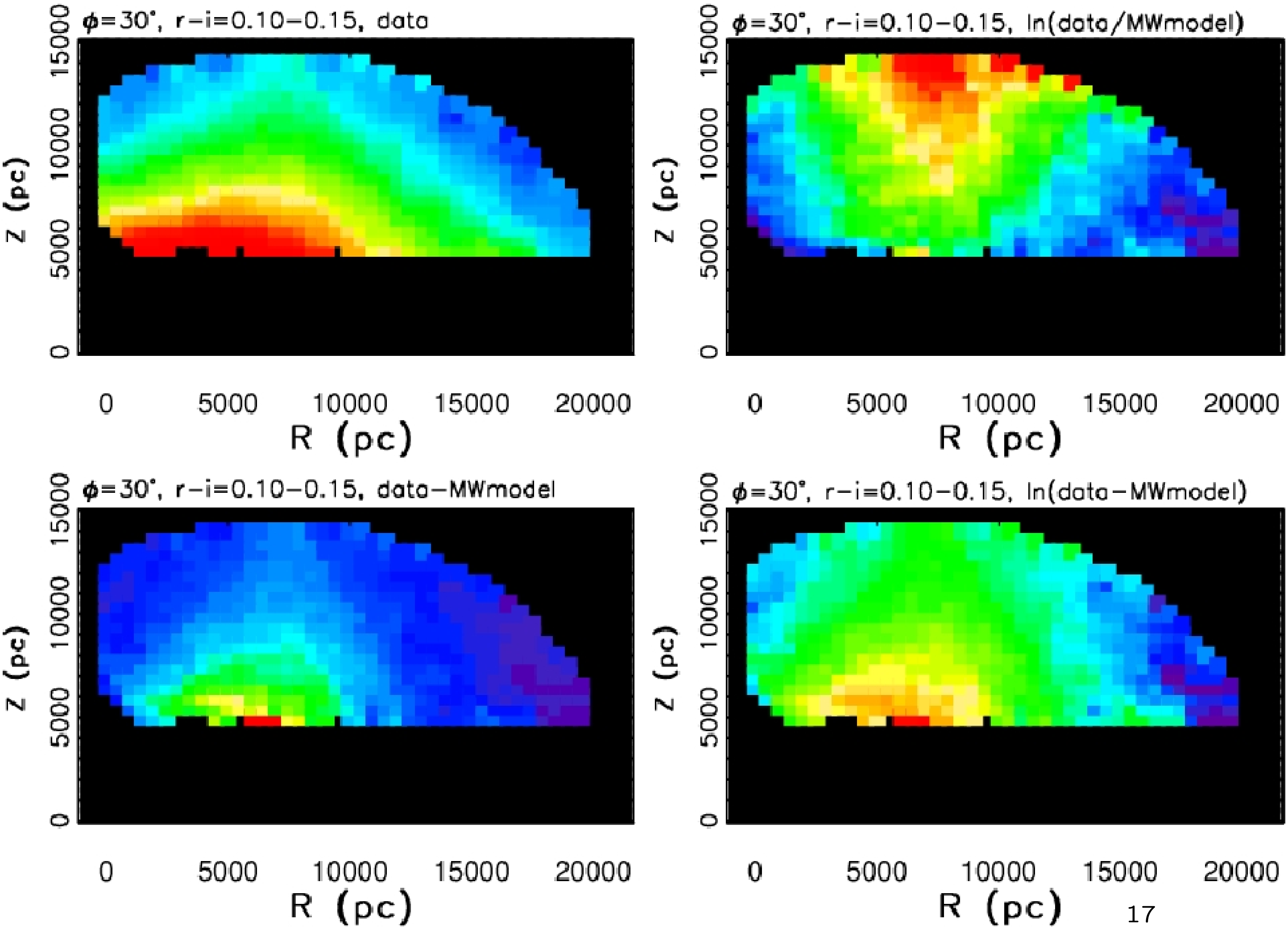
- Halo "flaring"?

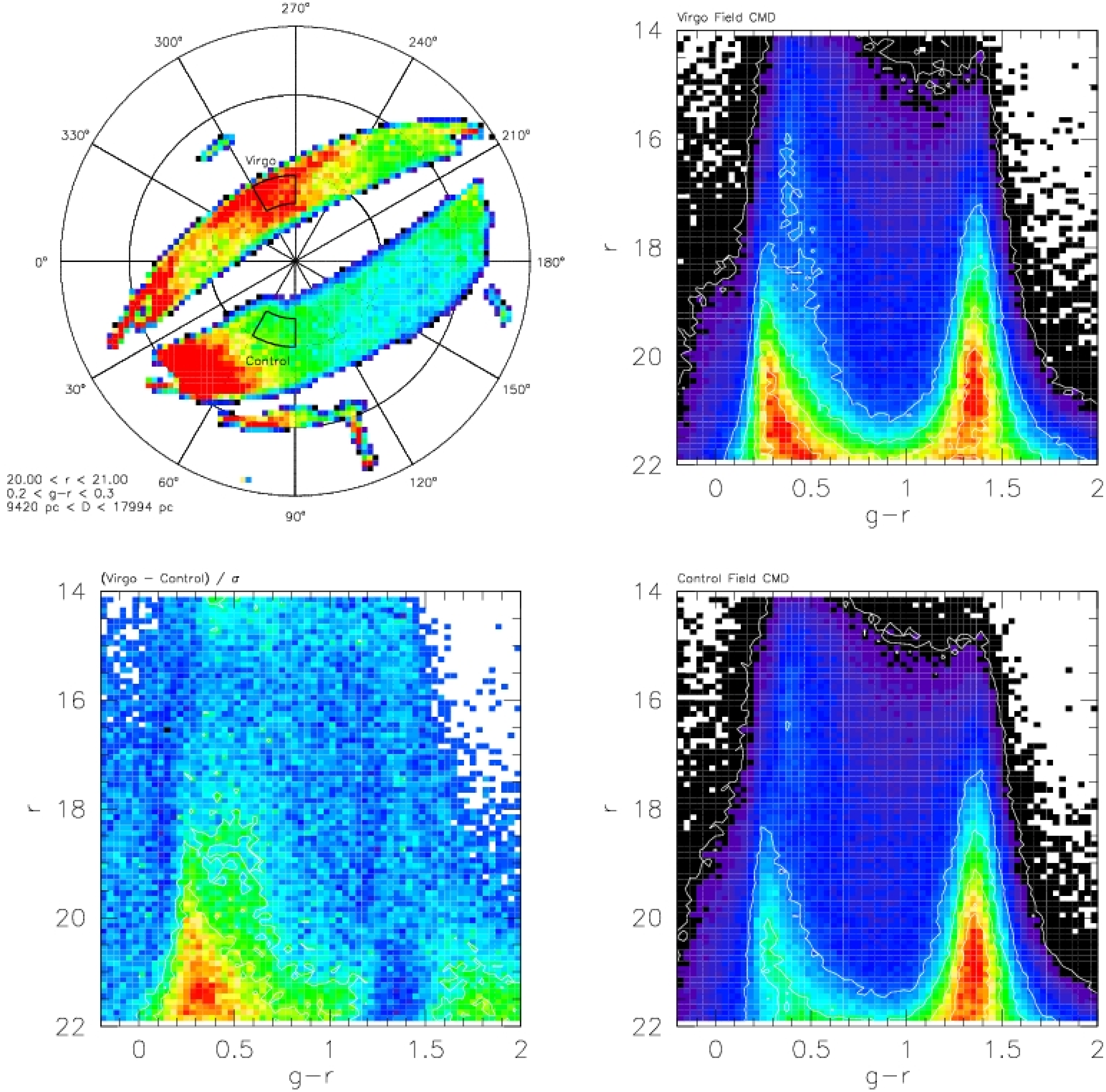
- 20-40 clumps expected within the whole disk (have we found the "missing satellites"?)

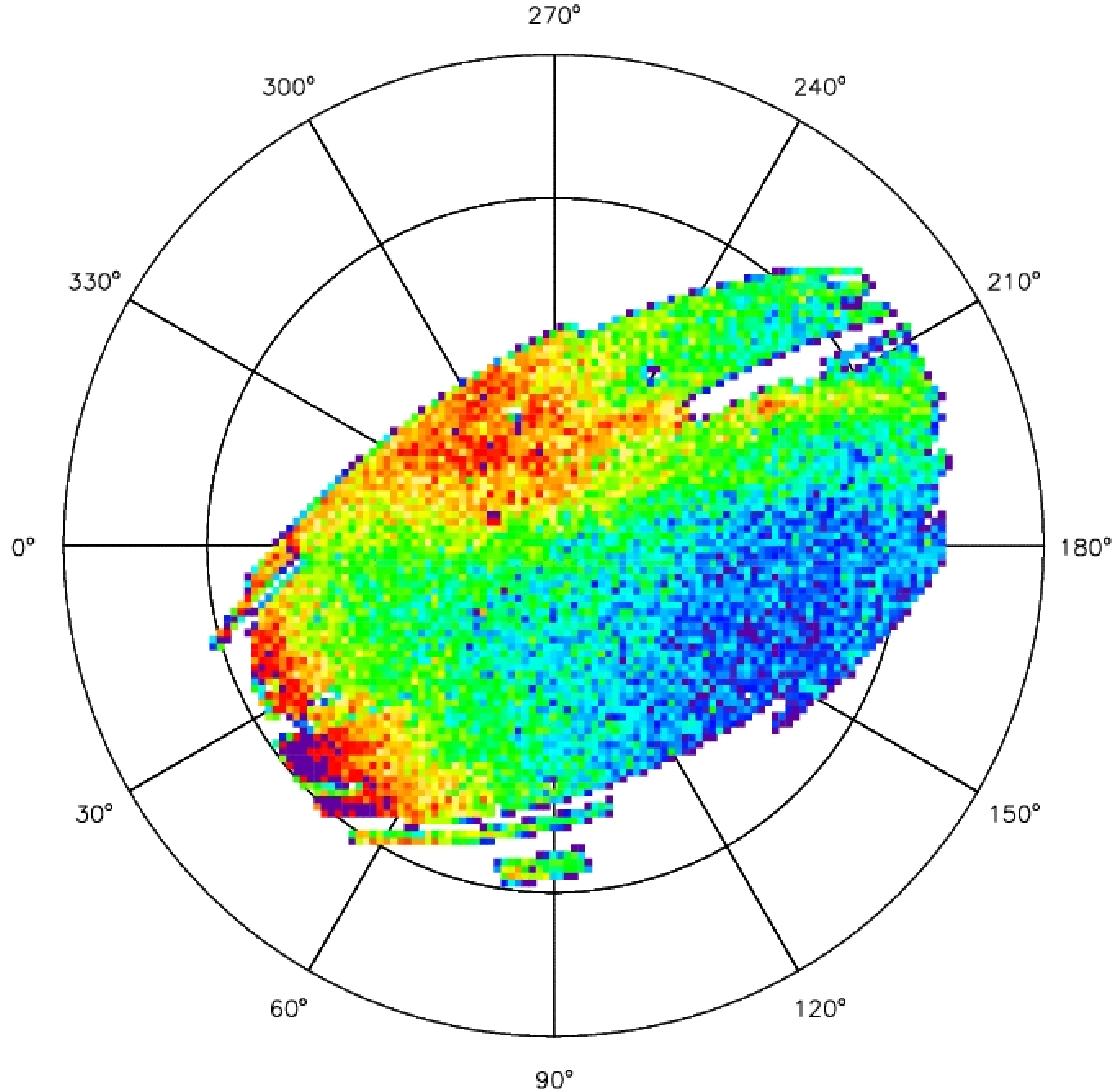


mean0.10 (0.10 < r − i < 0.15)
A
R [pc]
z [pc]
Data: Z = 10000 (0.10 < r−i < 0.15)
B
X (pc)
Y (pc)
z = +05000 pc (0.1 < r−i < 0.15)
z = +04000 pc (0.1 < r−i < 0.15)
z = +03000 pc (0.1 < r−i < 0.15)
X [pc]
Y [pc]

Large Virgo Overdensity




270°
300°
240°
330°
210°
0°
180°
30°
150°
60°
120°
90°
Virgo
Control
20.00 < r < 21.00
0.2 < g−r < 0.3
9420 pc < D < 17994 pc
Virgo Field CMD
(Virgo − Control) / σ
Control Field CMD
r
g−r
14
16
18
20
22
0
0.5
1
1.5
2



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

Summary

- 3D stellar number density maps of the Milky Way from SDSS photometric observations of $\sim$50 million stars

- A two-component exponential disk model is in fair agreement with the data

- Halo properties 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 $\sim$1000 deg^2 of the sky (see also Belokurov et al. 2006)

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

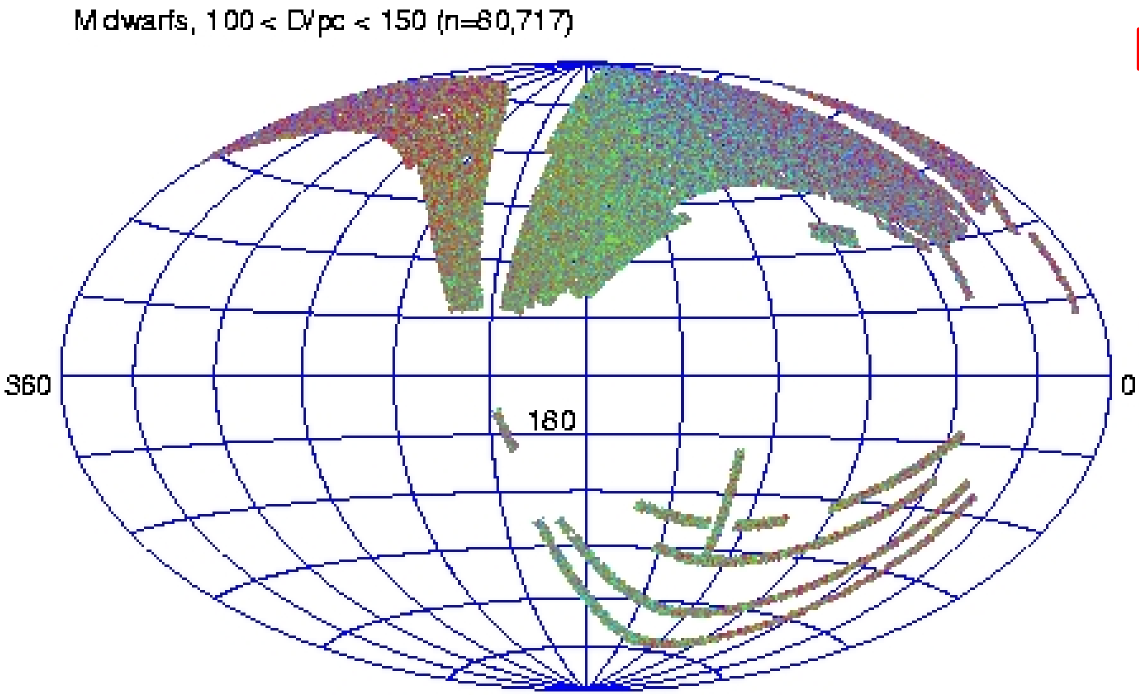
The SDSS Kinematics Data

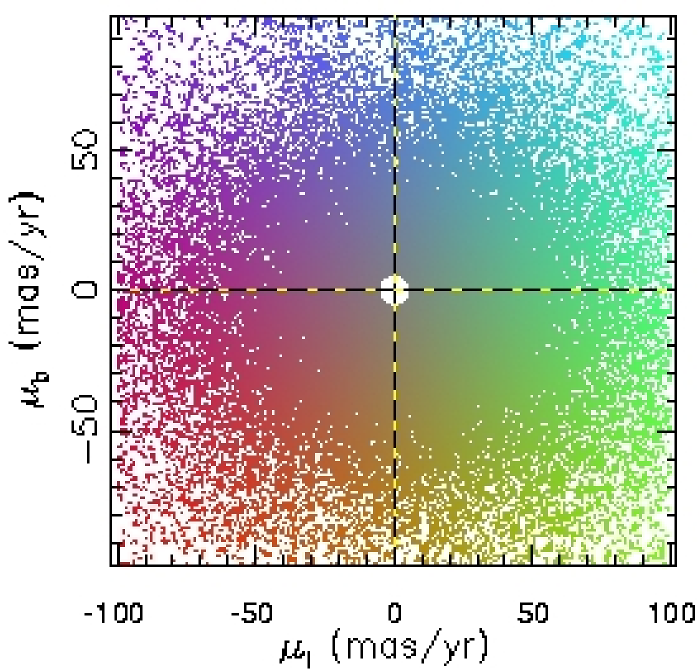
- SDSS has already obtained over 200,000 stellar spectra, with radial velocities accurate to $\sim$10 km/s, from nearby thin disk stars to outer halo

- SDSS-POSS proper motions (50 yrs baseline), limited by the POSS astrometric accuracy (0.15 arcsec, recalibrated POSS astrometry using SDSS astrometry for galaxies by Munn et al.), resulting in proper motion accuracy of $\sim$3 mas/yr (15 km/s at 1 kpc); usable to $g \sim 20$ the best ever proper motion database

- SDSS-SDSS proper motions ($\sim$5 yrs baseline) accurate to $\sim$6 mas/yr (using only 2 epochs); usable to $g \sim 21$ (not explored yet except for LT dwarfs, Knapp et al.)

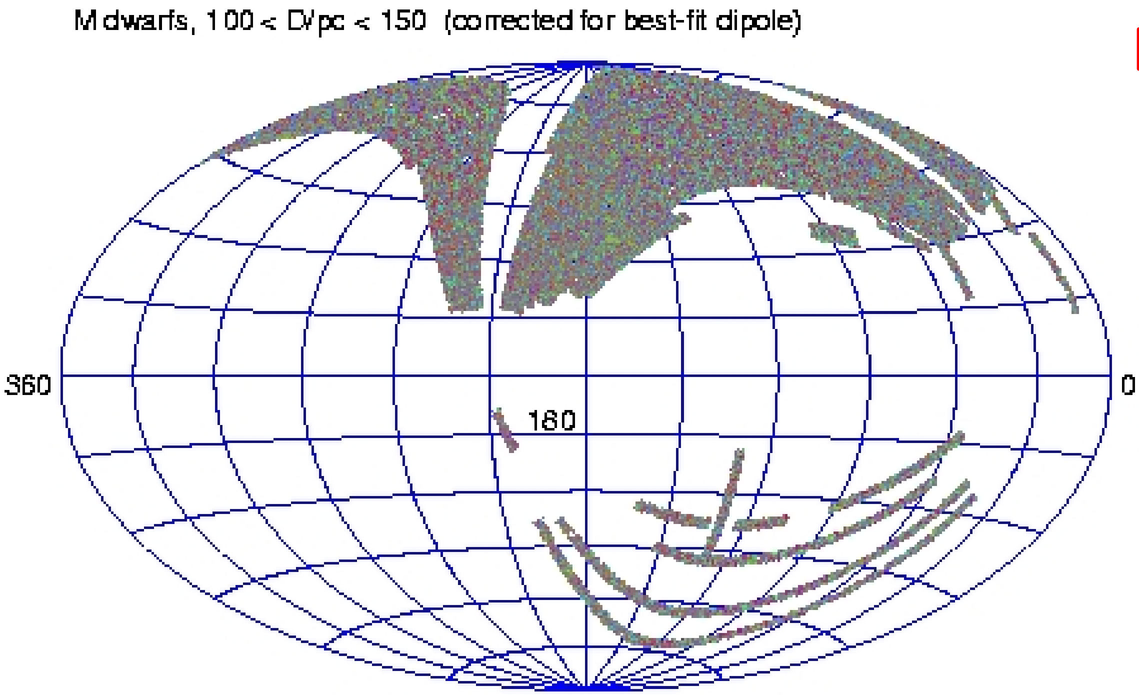
SDSS is revolutionizing kinematic studies of the Galactic structure   A preview of results from Bond et al. (2006)

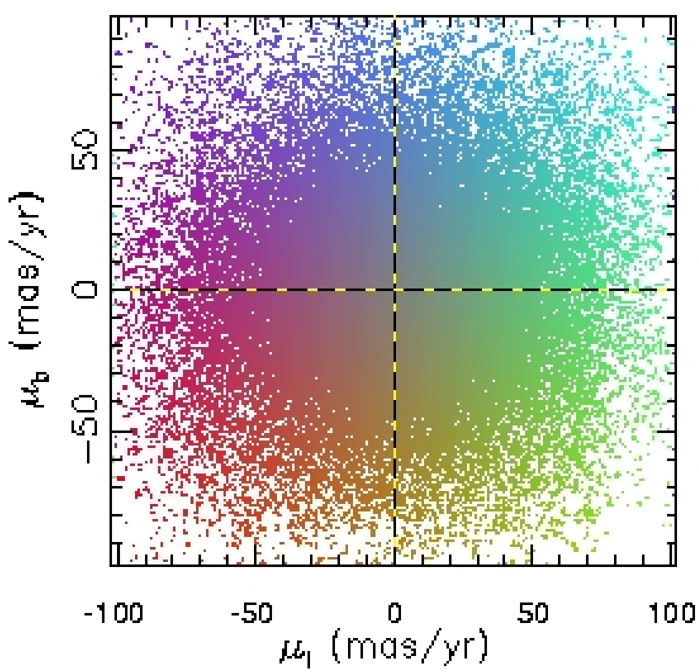




Nearby (<1 kpc) M dwarfs

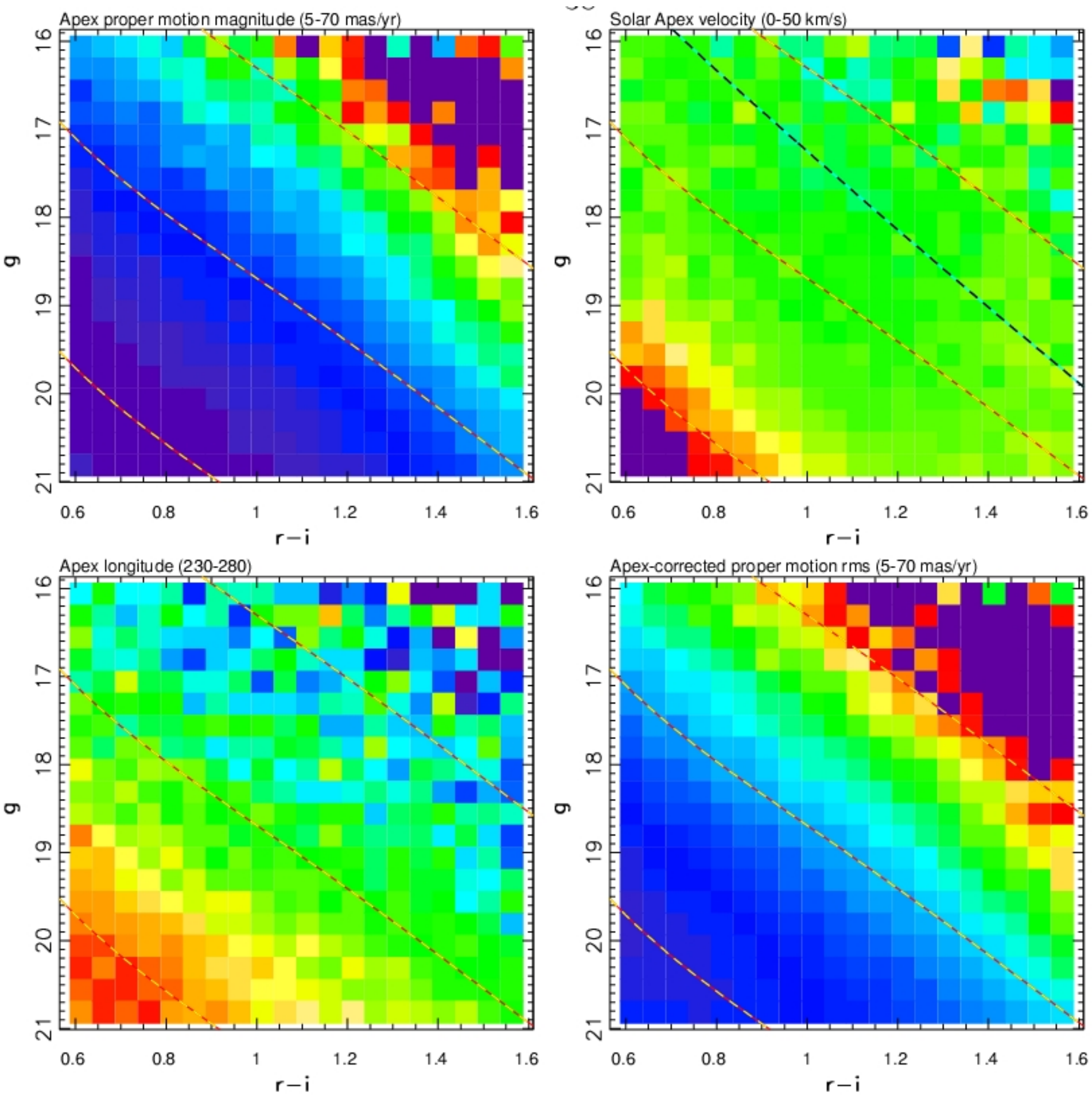
- Photometric parallax relation most robust for M dwarfs
- Left: Distribution of proper motion vectors (color coded according to the legend shown in the bottom panel) in Aitoff projections of galactic coordinates for a distance selected (100–150 pc) subsample of M dwafs
- A dipole distribution is evident: need to account for solar motion





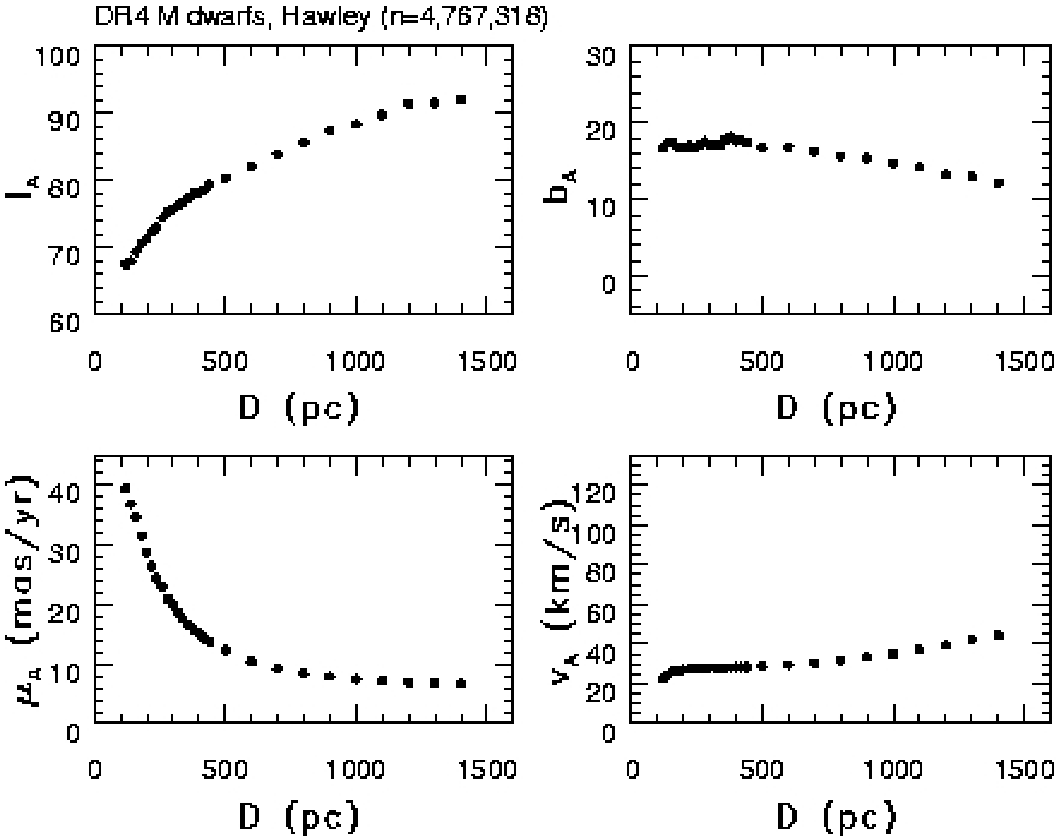
Nearby (<1 kpc) M dwarfs

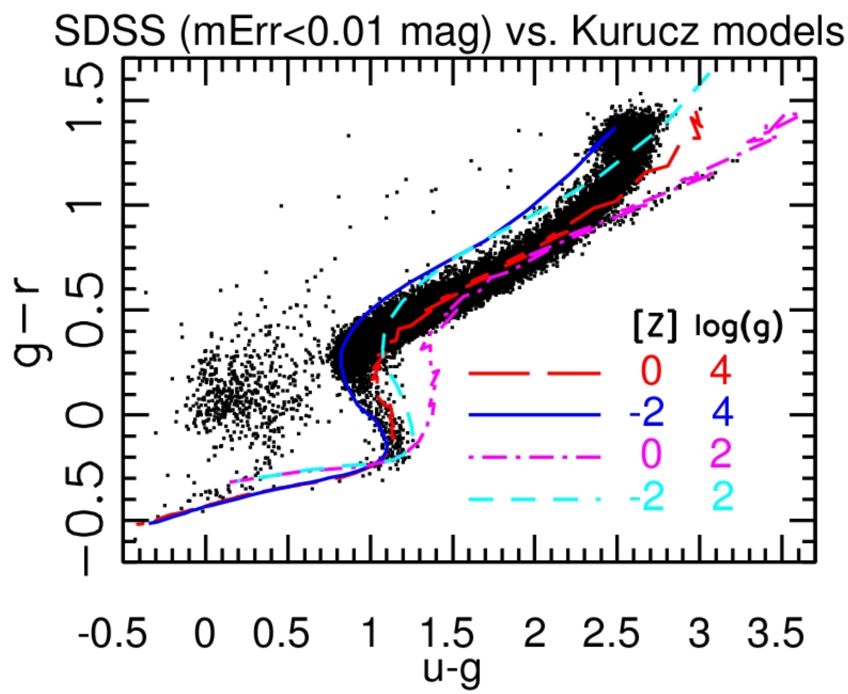
- Left: Distribution of proper motion vectors after correction for solar motion
- One can fit dipole to small bins in the g vs. $r-i$ color-magnitude diagram
- This tests whether M dwarfs kinematics depend on the sub-sample distance (i.e. position in the Galaxy) (and also provides a sanity check on the adopted photometric parallax relation



Nearby (<1 kpc) M dwarfs

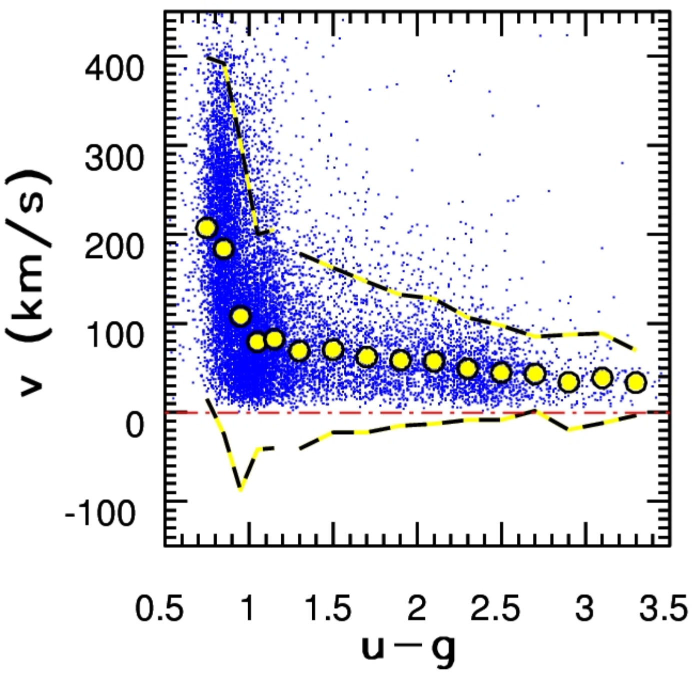
- **Top left:** apex proper motion magnitude
- Bottom left : apex longitude
- Top right: corresponding apex velocity
- Bottom right: apex-corrected root-mean-scatter for proper motion
- Conclusion 1: photometric parallax relation is robust
- Conclusion 2: kinematics change with distance, deviations noticable for $D \sim 1$ kpc!

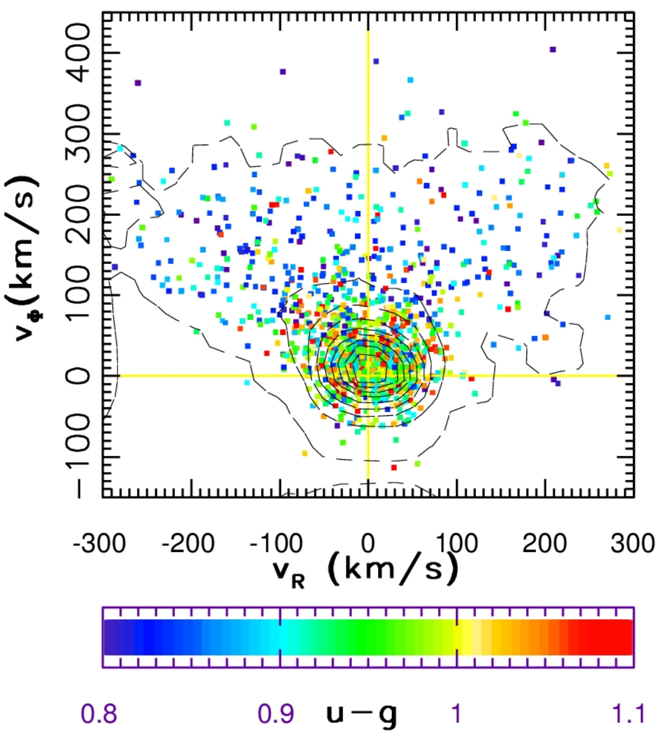




Nearby (<1 kpc) M dwarfs

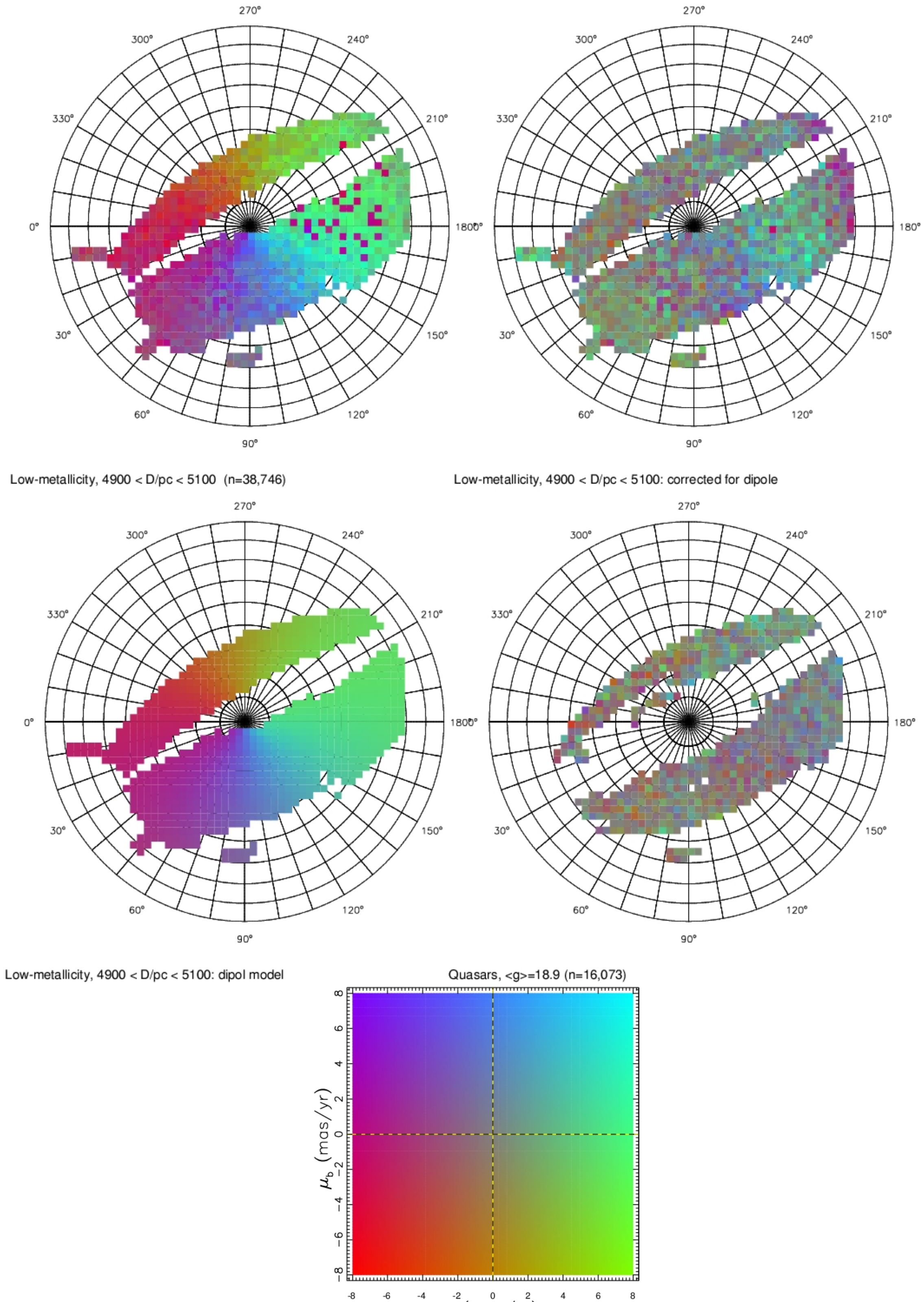
- **Top left:** apex parameters as a function of distance
- The relative (rotational) velocity (middle right panel) increases with distance
- Is this increase due to a dependence on R, Z, or both?
- Does this increase continue beyond 1 kpc?
- We can probe more distant regions with more luminous (bluer) stars – but need to be careful about metallicity
- **Bottom left:** Kurucz model predictions as a function of metallicity and gravity: the blue tip of the main stellar locus is populated ONLY by low-metallicity stars





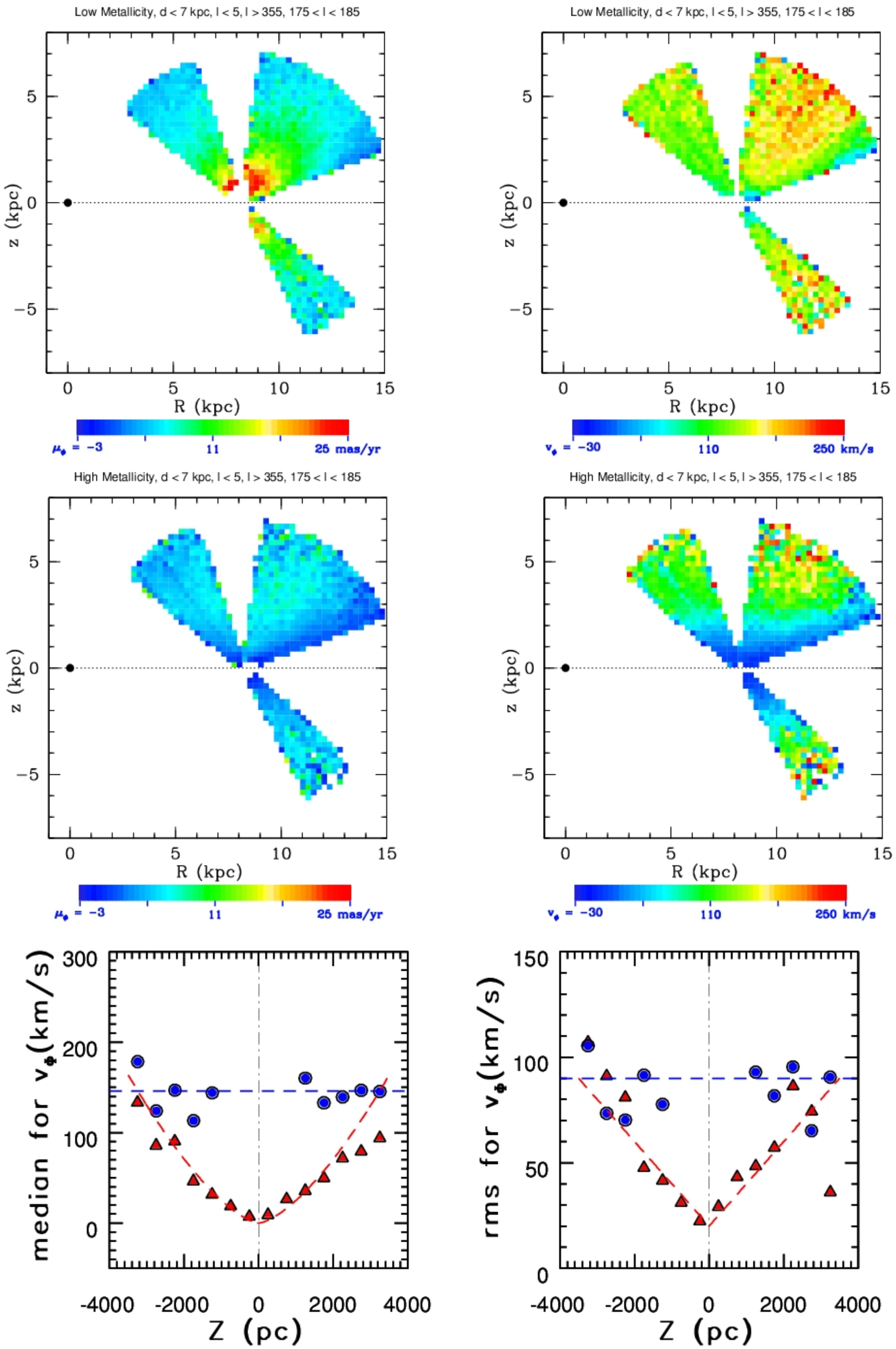
Color – Metallicity – Kinematics Correlations

- **Top left:** the dependence of the velocity magnitude on the $u - g$ color for 6D stars with 14.5 $< r <$ 18.5
- **Bottom left:** The rotational vs. radial velocity component color-coded by the $u - g$ color
- The kinematics markedly change at $u - g = 1$
- Only $u - g < 1$ stars can have $|v_R|$ >100 km/s; they also have $< v_\phi$ ~200 km/s
- This has been known for over half a century (since ELS), but reproduced here with a 100 times larger sample!
- With SDSS samples, we can study ELS conclusions as a function of the position in the Galaxy! (i.e. not only in the solar neighborhood)



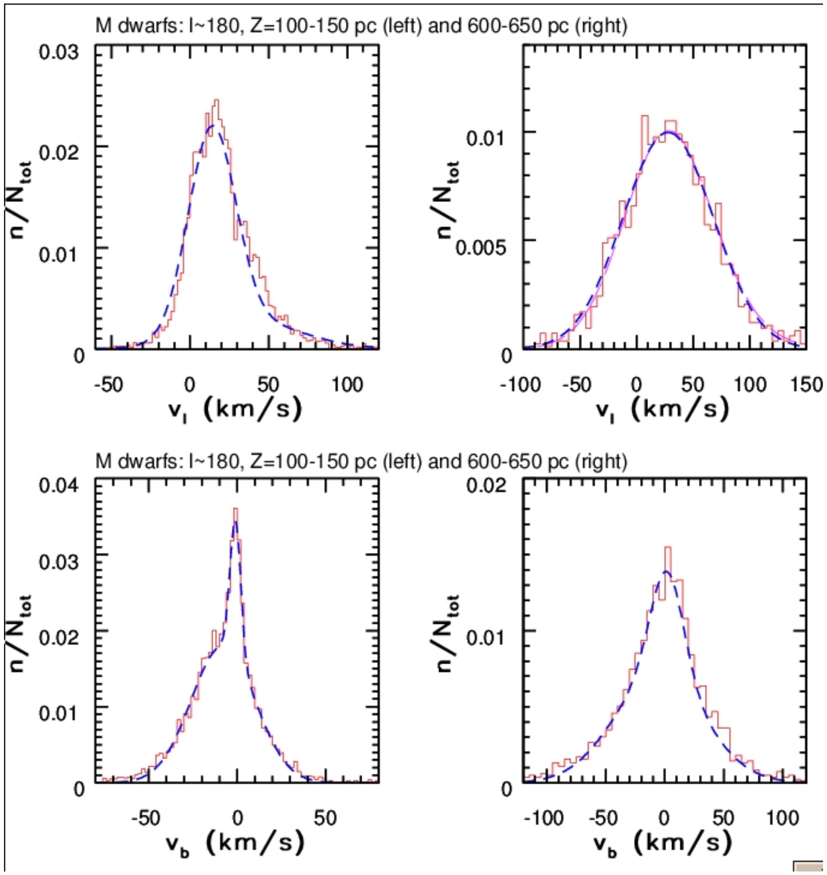
Kinematics with Proper Motions Only

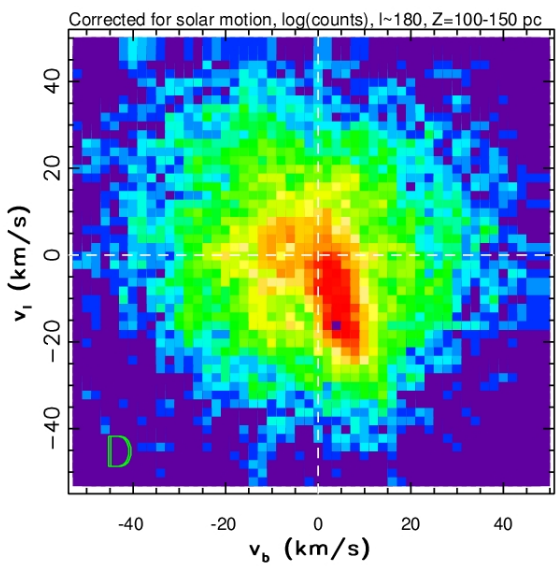
- Top left: measured proper motion vectors for **low-metallicity** stars at 5 kpc, 2D color-coded according to the legend in the bottom panel
- Middle left: A dipol model (essentially due to solar motion)
- Top right: (data-model) residuals; proper motion scale increased by a factor of 2; note the large coherent structure around $l \sim 180$ (right part)
- Middle right: limits on systematic errors from spectroscopically confirmed SDSS quasars



Halo vs. Disk(s) Kinematics

- **Top left:** longitudinal proper motion in the Y=0 plane ($l \sim 0$ and $l \sim 180$ plane) for low-metallicity stars; color-coded linearly from blue (small) to red (large)
- **Top right:** rotational velocity corresponding to the top right panel
- **Middle left:** longitudinal proper motion in the Y=0 plane ($l \sim 0$ and $l \sim 180$ plane) for high-metallicity stars
- **Middle right:** rotational velocity corresponding to the top bottom panel
- Note the difference between the top and middle panels, summarized in the bottom row!





Halo vs. Disk(s) Kinematics

- When looked in detail, kinematic structure is more complex than, e.g., Schwarzschild (Gaussian) velocity distribution, and the normalization of individual components is inconsistent with relative normalization inferred from counts
- Standard kinematic models cannot explain the data.
- Preliminary comparisons with N-body simulations show encouraging level of agreement.

Grand Summary

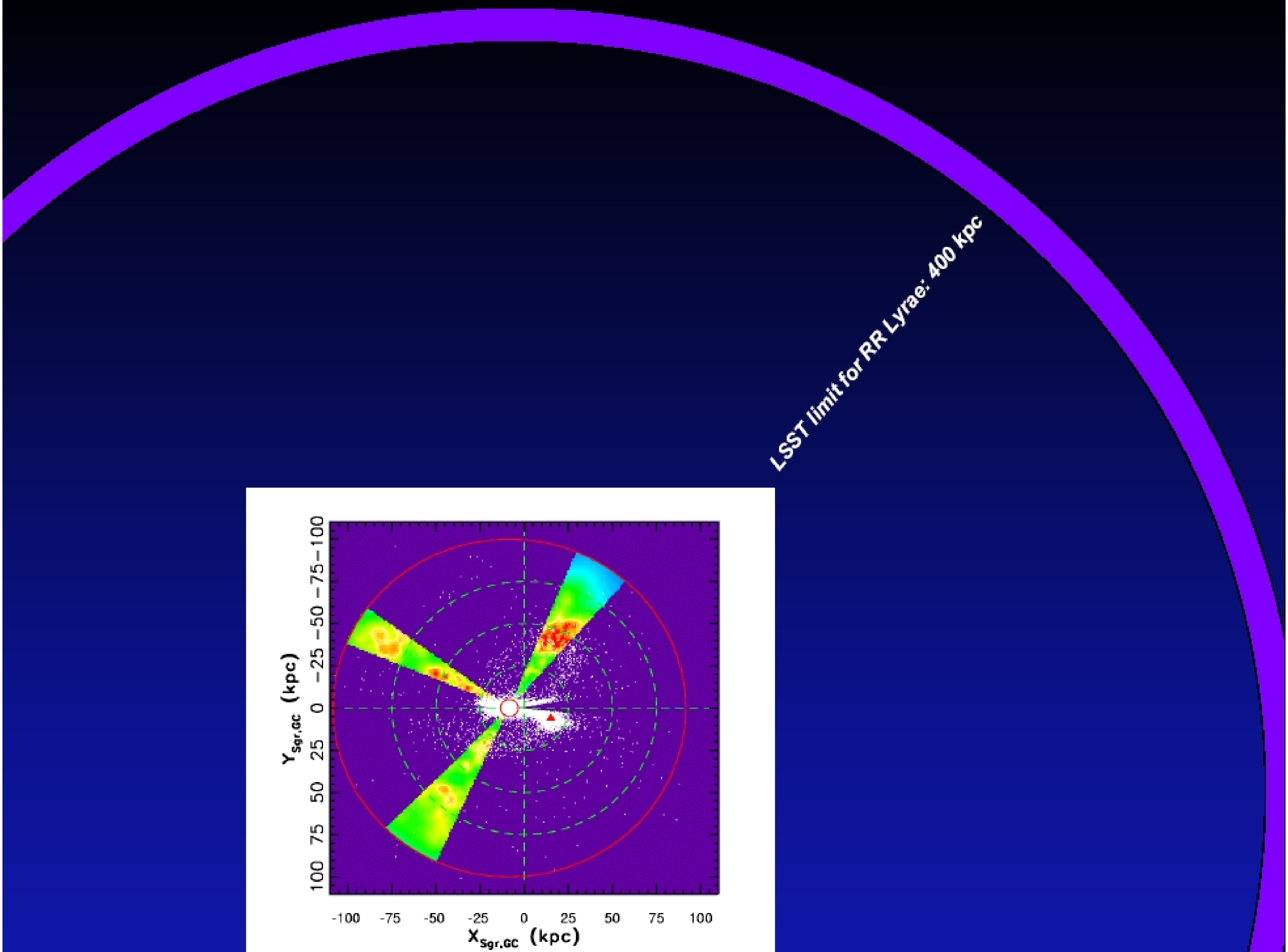
- Clumps/overdensities/streams are an integral part of Milky Way structure, both of halo and the disk(s); and similar complexity is seen in the Milky Way kinematics

- High-metallicity stars have smoothly increasing rotational lag and velocity dispersion with the distance from the plane (Z)

- The dependence of the rotational lag on the height above the plane dominates over the radial gradient

- Kinematics structure is **at least** as complex as the spatial structure.

SDSS is revolutionizing studies of the Galactic structure; Pan-STARRS and LSST will do even better!


LSST limit for RR Lyrae: 400 kpc
-100 -75 -50 -25 0 25 50 75 100
X_Sgr,GC (kpc)
Y_Sgr,GC (kpc)

Large Synoptic Survey Telescope

- LSST = d(SDSS)/dt: an 8.4m telescope with single exposures reaching V$\sim$24.5 over a 9.6 deg^2 FOV: the whole (observable) sky in two bands every three nights

- LSST = Super-SDSS: an optical/near-IR survey of the observable sky in multiple bands (grizY) to V$>$27.5 (coadded)

Science Drivers

- Dark Energy and Dark Matter (through weak lensing, SNe Ia, clusters)
- The Milky Way Map (main sequence to 150 kpc, RR Lyrae to 400 kpc, geometric parallaxes for all stars within 500 pc)
- The Solar System Map (over a million main-belt asteroids, $\sim$100,000 KBOs, Sedna-like objects to beyond 150 AU)
- The Transient Universe (a variety of time scales ranging from $\sim$10 sec, to the whole sky every 3 nights)

Large Synoptic Survey Telescope