Astr 509: Astrophysics III: Stellar Dynamics

Winter Quarter 2005, University of Washington, Željko Ivezić

Lecture 1:

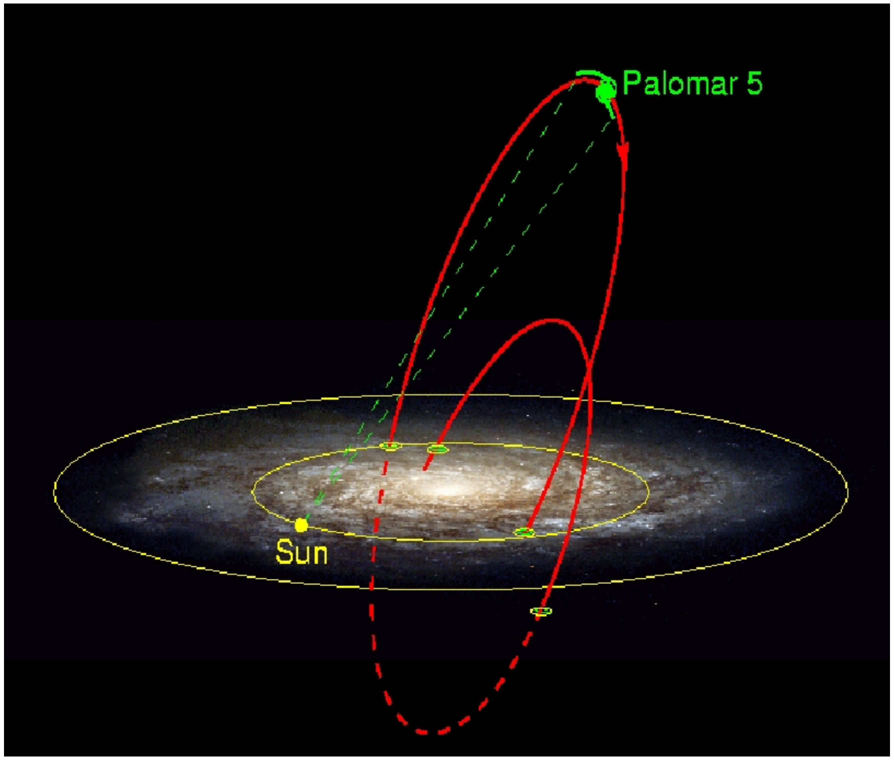
Basic Model of the Milky Way, Galaxies

The Basics of Basics

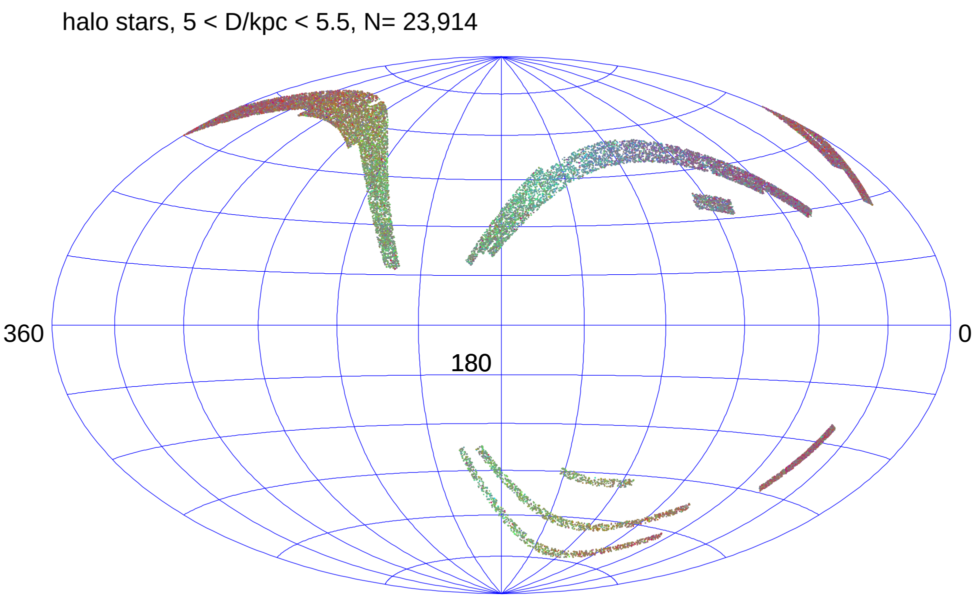
Assumed that you are all familiar with these terms:

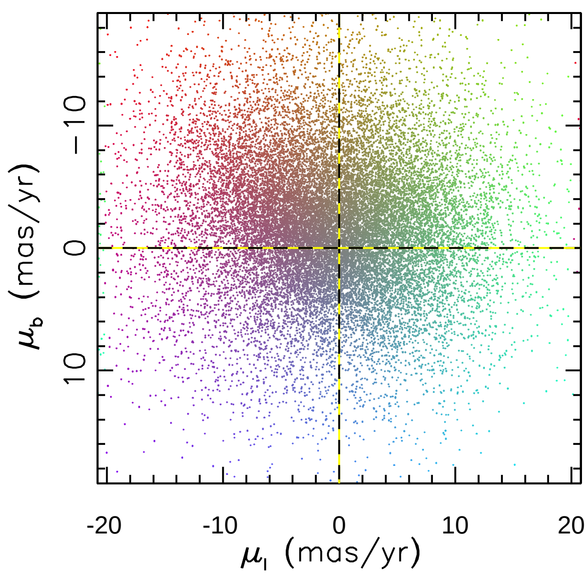
- effective temperature, spectral class
- distance modulus, absolute magnitude, bolometric luminosity
- HR diagram
- white dwarfs, horizontal branch, red giants, supergiants, sub-giants, subdwarfs
- galactic coordinates

The Basic Milky Way Model



- Disk(s): population I, exponential (?) disks, thin and thick, rotating, lots of gas and dust, star-forming, spiral arms, bar
- Spheroid (nucleus, bulge, halo): population II, out to ~100 kpc, roughly a power-law, made of stars (different metallicity and kinematics than disk stars), globular clusters, no evidence for gas and dust
- Is there structure in the outer halo? Monolithic collapse (Eggen, Lynden-Bell & Sandage 1962) vs. merger scenario (Searle & Zinn 1978)

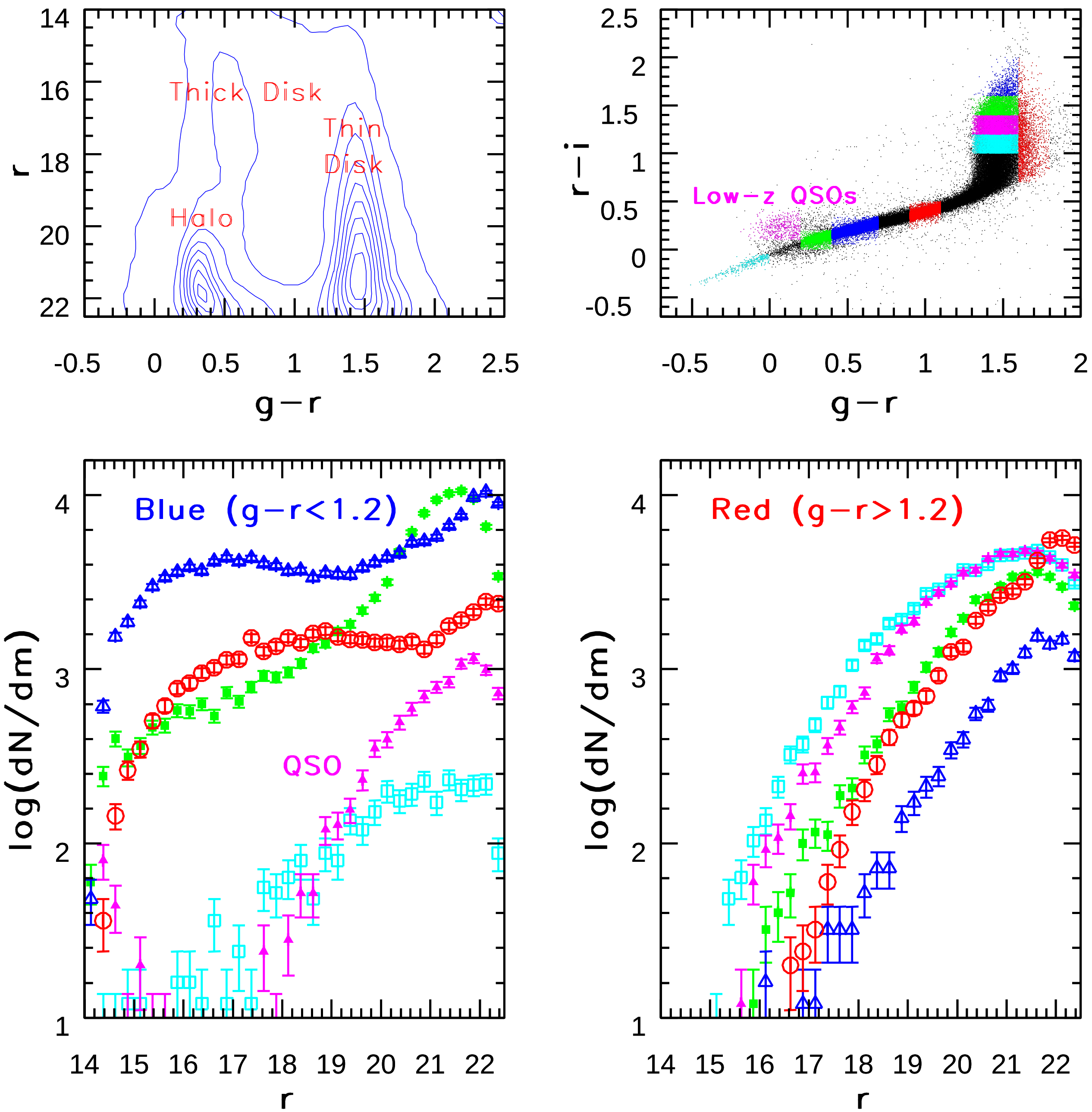




The Milky Way Kinematics

- There are three velocity components; ideally, we'd like to know their distributions as a function of the position in the Galaxy (to the first order, the disk rotates and the halo doesn't)
- Standard description: Schwarzschild's velocity ellipsoid (Gaussian distributions)
- Solar peculiar motion, the local standard of rest, asymmetric drift
- Circular-speed curve: $v_c(R|z{=}0)$; $v_c(R_\odot{\sim}8.5\ \mathrm{kpc}){=}220{\pm}15$ km/s
- Oort's constants: measure $v_c(R_\odot)$ and $(dv_c/dR)|_{R=R_\odot}$

9 epochs, unresolved, n=216830, psf mags, area=60 deg^2



Stellar Counts

There is a lot of information about the Milky Way structure (and stellar initial mass function, and stellar evolution) in SDSS imaging data.

How can we extract and interpret this information? What is the meaning of local maxima in the differential counts for some (but not all) color cuts?

Computing Differential Stellar Counts $n(m)$

1. $n(m) = dN/dm = dN/dV \, dV/dm$,
   $dN/dV = \rho(l, b, D)$ (ρ constrains Galactic Model)

2. For a pencil beam: $dV = \Delta\Omega \, D^2 \, dD$

3. $D = 10\text{pc}\, 10^{0.2(m-M)}$, $dD/dm = 0.2 \, ln(10) \, D(m)$

4. $n(m) = \rho(l, b, m) \, 0.2 \, \Delta\Omega \, ln(10) \, (10 \, pc)^3 \, 10^{-0.6M} \, 10^{0.6m}$

$$n(m) \propto \rho(l, b, m) \, 10^{0.6m}$$

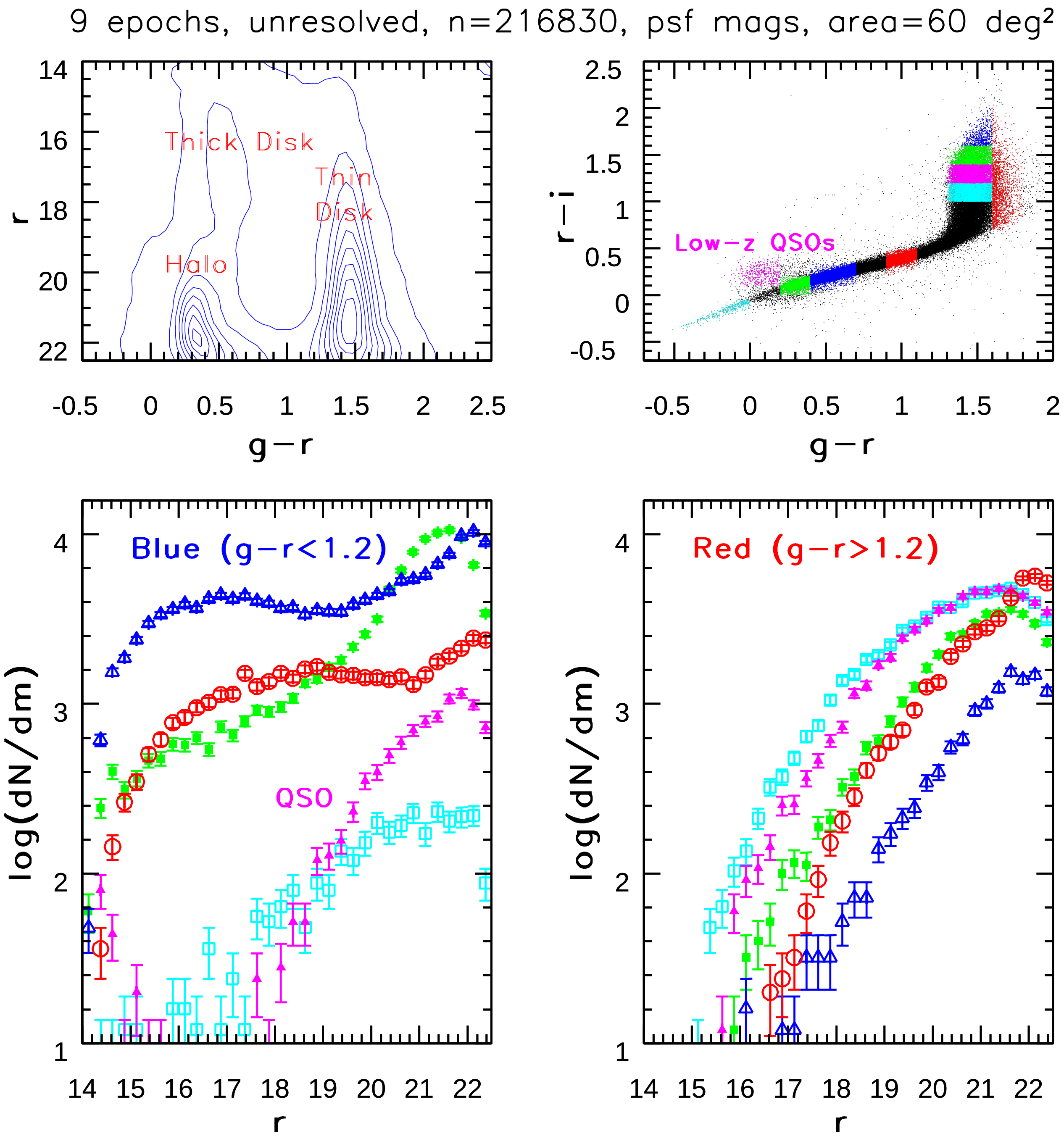
Examples for $n(m) \propto \rho(l,b,m)\,10^{0.6m}$

- Power-law: $\rho(l,b,D) \propto D^{-n}$

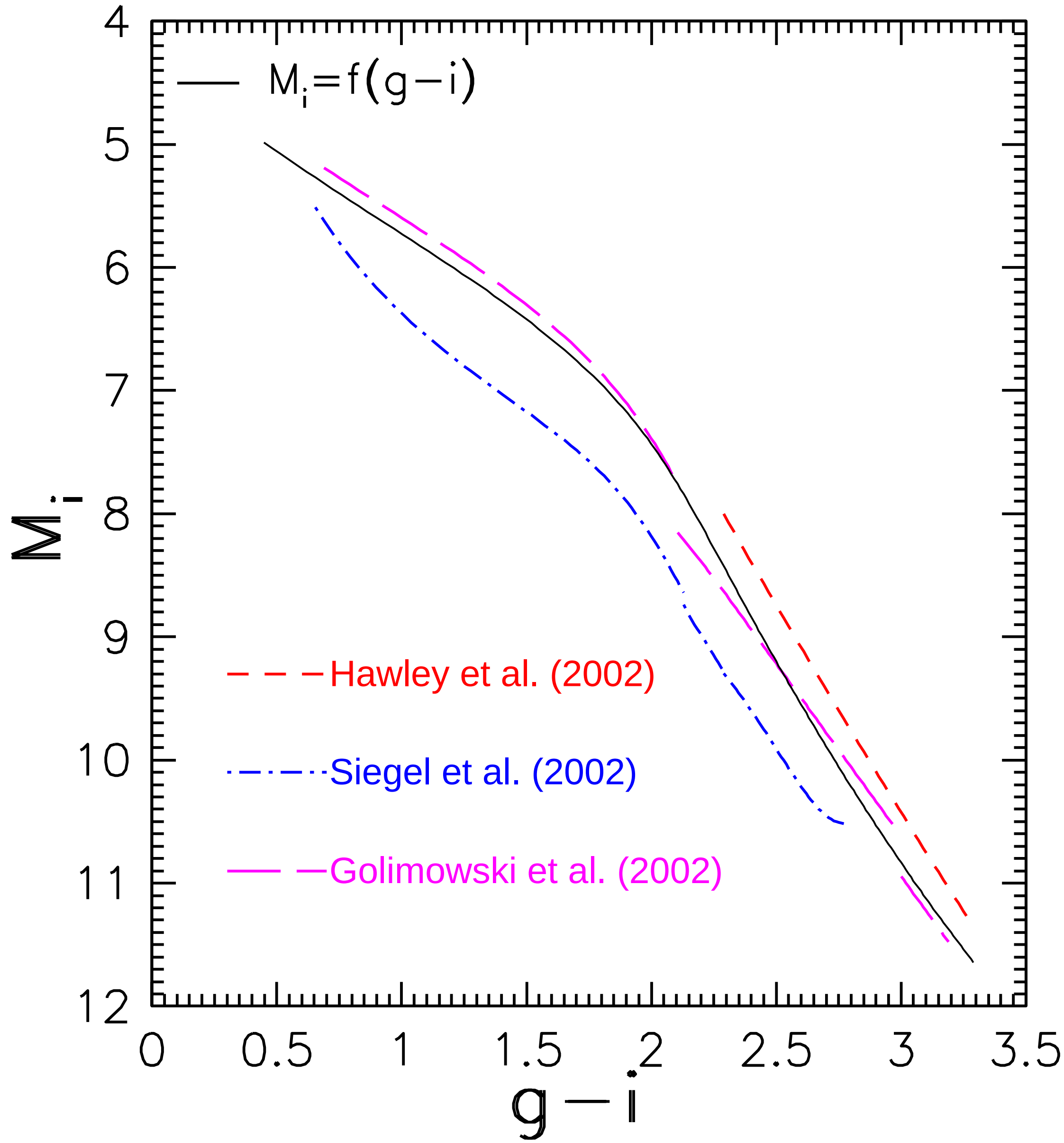
$$n(m) \propto 10^{k\,m},\ k = 0.6 - 0.2\,n$$

  - Euclidian counts (n=0): $n(m) \propto 10^{0.6\,m}$,
  - Halo counts (n=3): $n(m) = const.$

- Exponential disk: $\rho(l,b,D) \propto e^{-D/H}$
  at a distance $D = k\,H$, $n(m)$ has a local slope corresponding to a power-law with $n = k$. Hence, for $D = 3\,H$, the differential counts for exponential density distribution have a local maximum!



9 epochs, unresolved, n=216830, psf mags, area=60 deg²
Thick Disk
Thin Disk
Halo
r
g−r
r−i
Low−z QSOs
Blue (g−r<1.2)
QSO
log(dN/dm)
Red (g−r>1.2)



$M_i = f(g-i)$
Hawley et al. (2002)
Siegel et al. (2002)
Golimowski et al. (2002)
M_i
$g-i$
4
5
6
7
8
9
10
11
12
0
0.5
1
1.5
2
2.5
3
3.5

What are SDSS counts telling us?

- For $g - r \sim 0.5$, maximum for $n(m)$ at $r = 17$
  $g - r \sim 0.5$ implies $g - i \sim 0.8$ and $M_r \sim 5.7$: $H' \sim 1800kpc$

- For $r - i \sim 1.5$, maximum for $n(m)$ at $r = 21.5$
  $r - i \sim 1.5$ implies $g - i \sim 2.9$ and $M_r \sim 12$: $H' \sim 800kpc$

- $H' = H/\sin b \sim 2\,H$, in agreement with expectations for thin ($H \sim 300$pc) and thick ($H \sim 1.0$kpc) disks.

- With SDSS we can do better than with this standard approach because the vast majority ($\sim 98 - 99\%$) of detected stars are on the main sequence and the photometry is very accurate.

Dissecting Milky Way with SDSS

- Standard 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?

Dissecting Milky Way with SDSS

- Standard 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?

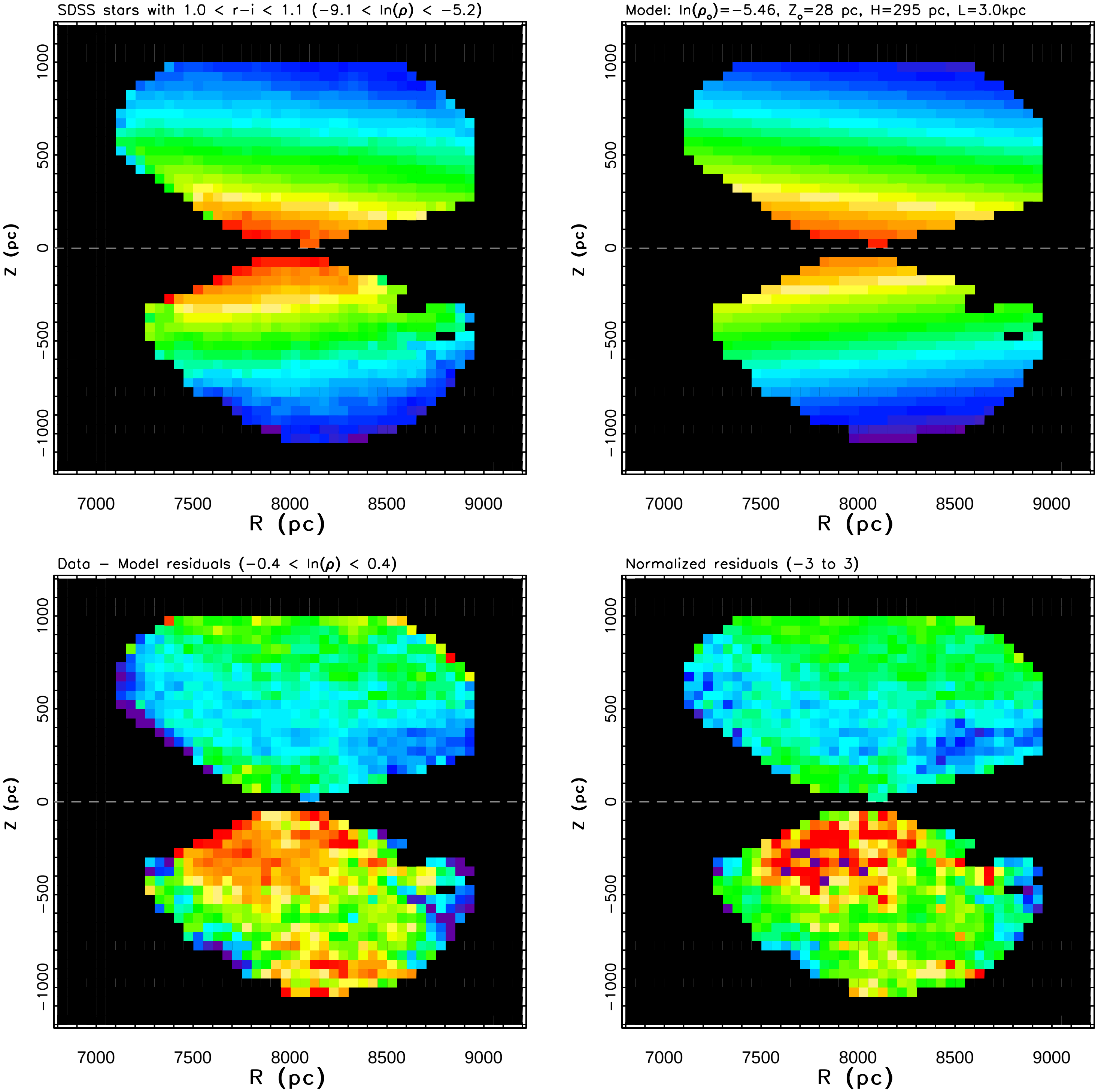
- The vast majority of stars detected by SDSS are on the main sequence: stars in a narrow color bin all have about the same luminosity, and this luminosity can be estimated from photometric parallax relation.

Dissecting Milky Way with SDSS

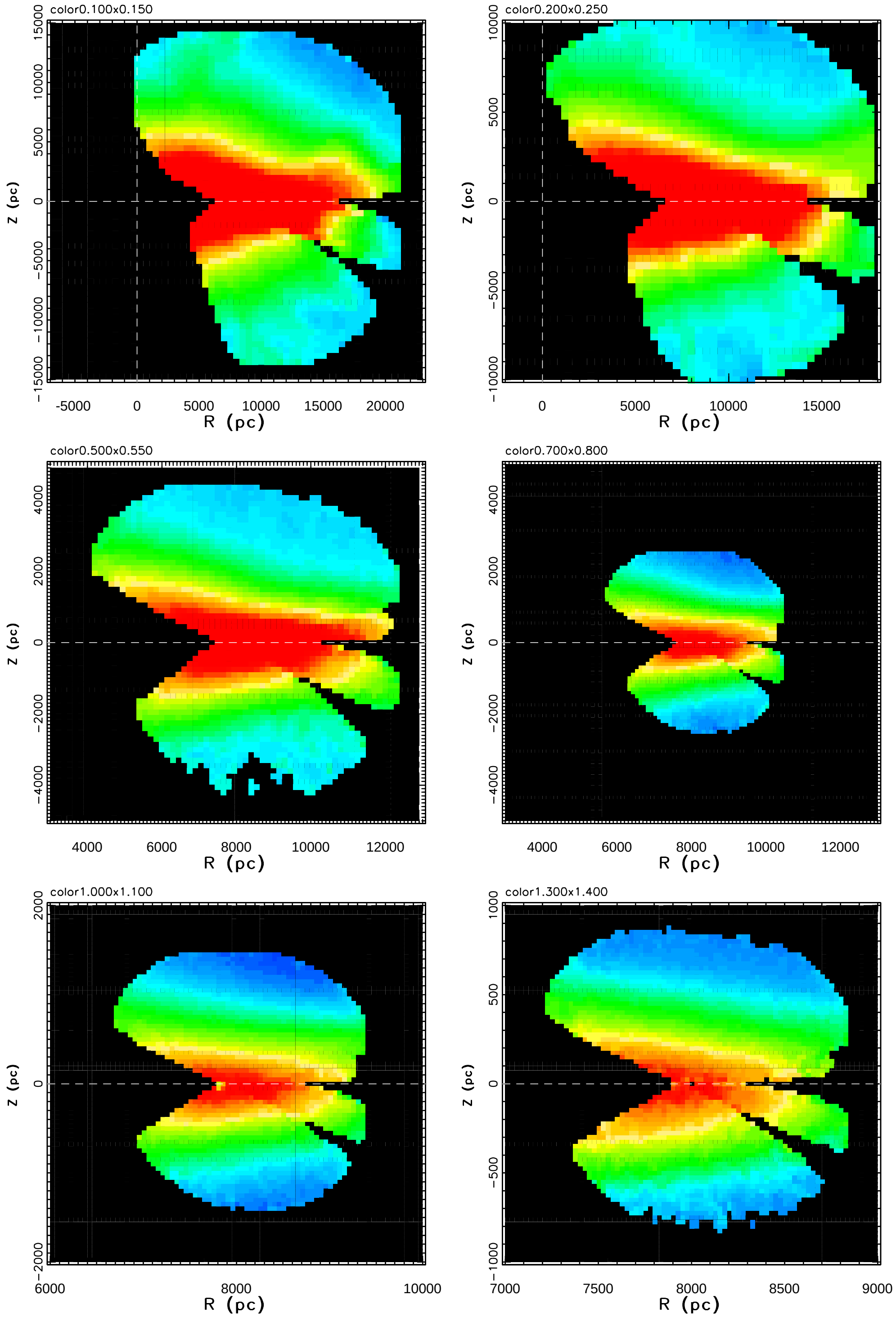
- Standard approach: assume initial mass function, fold with models for stellar evolution; assume mass-luminosity relation; assume some parametrization for the number density distribution; vary (numerous) free parameters until the observed and model counts agree. Uniqueness? Validity of all assumptions?

- The vast majority of stars detected by SDSS are on the main sequence: stars in a narrow color bin all have about the same luminosity, and this luminosity can be estimated from photometric parallax relation.

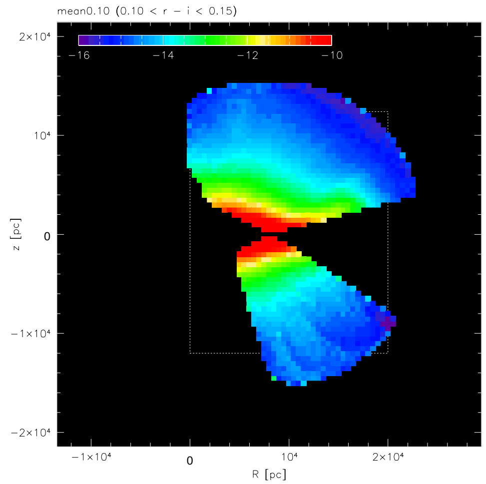
- Since the distance to each star is known, its 3-dimensional position (X, Y, Z, or R, z, ϕ) in the Galaxy is known: direct determination of the stellar number density

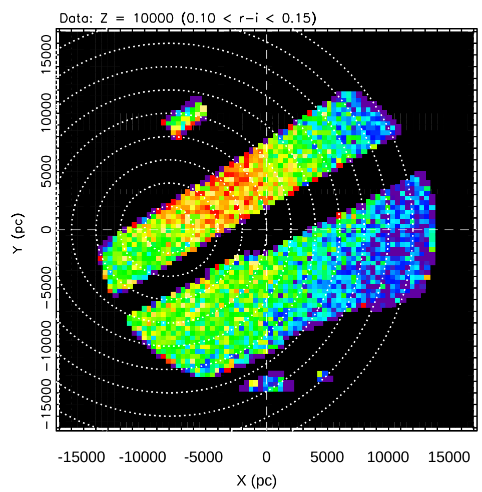


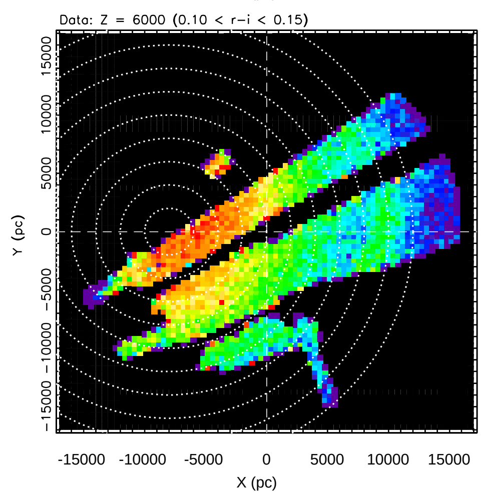
SDSS stars with 1.0 < r−i < 1.1 (−9.1 < ln(ρ) < −5.2)
Model: ln(ρ$_o$)=−5.46, Z$_o$=28 pc, H=295 pc, L=3.0kpc
Data − Model residuals (−0.4 < ln(ρ) < 0.4)
Normalized residuals (−3 to 3)
Z (pc)
R (pc)

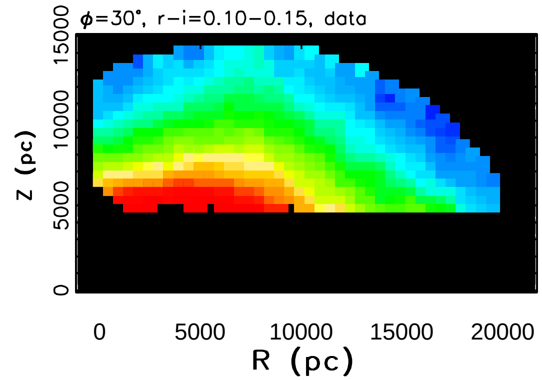


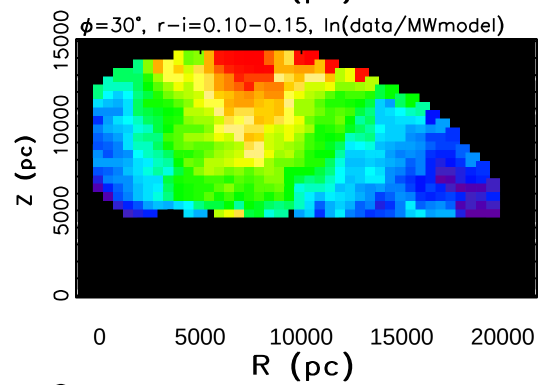
color0.100x0.150
color0.200x0.250
color0.500x0.550
color0.700x0.800
color1.000x1.100
color1.300x1.400
Z (pc)
R (pc)

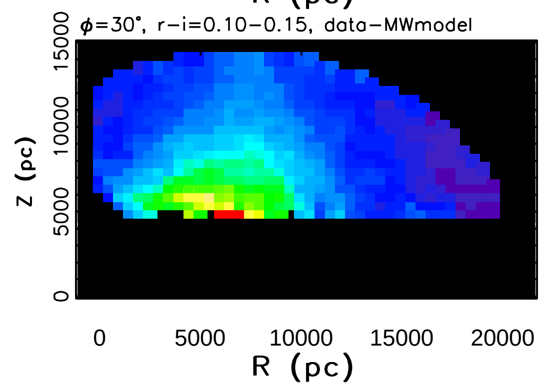

mean0.10 (0.10 < r − i < 0.15)
−16 −14 −12 −10
z [pc]
R [pc]

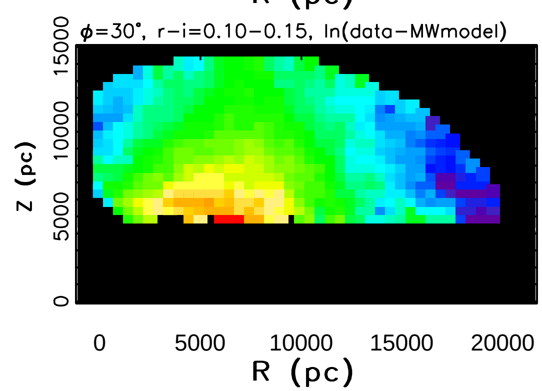

Data: Z = 10000 (0.10 < r−i < 0.15)
Y (pc)
X (pc)


Data: Z = 6000 (0.10 < r−i < 0.15)
Y (pc)
X (pc)


ϕ=30°, r−i=0.10−0.15, data
Z (pc)
R (pc)


ϕ=30°, r−i=0.10−0.15, ln(data/MWmodel)
Z (pc)
R (pc)


ϕ=30°, r−i=0.10−0.15, data−MWmodel
Z (pc)
R (pc)


ϕ=30°, r−i=0.10−0.15, ln(data−MWmodel)
Z (pc)
R (pc)

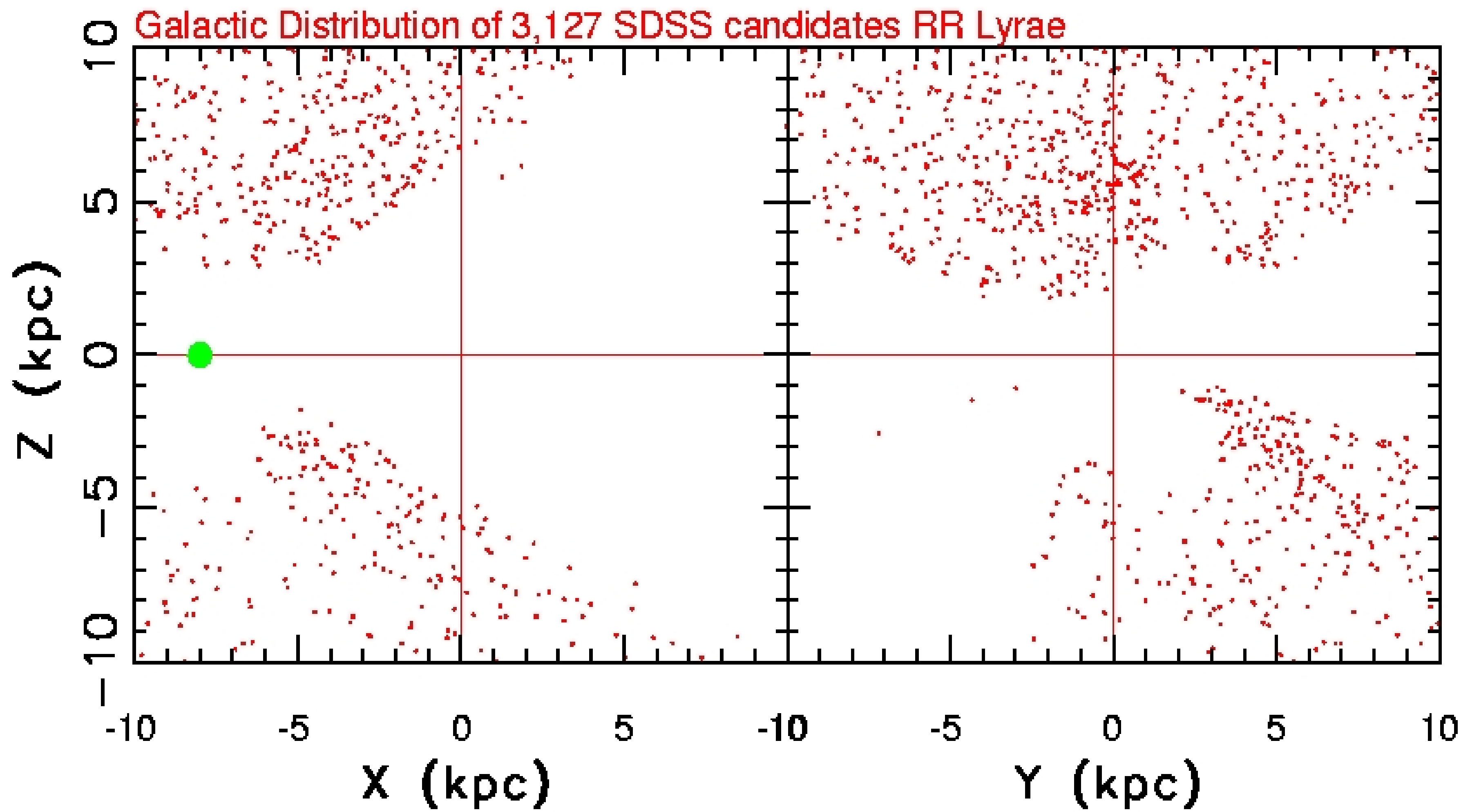
To Boldly Go Where None Has Gone Before

- Photometric parallax works for distances from $\sim$100 pc to $\sim$10 kpc. Can we see further out, say to $\sim$100 kpc?

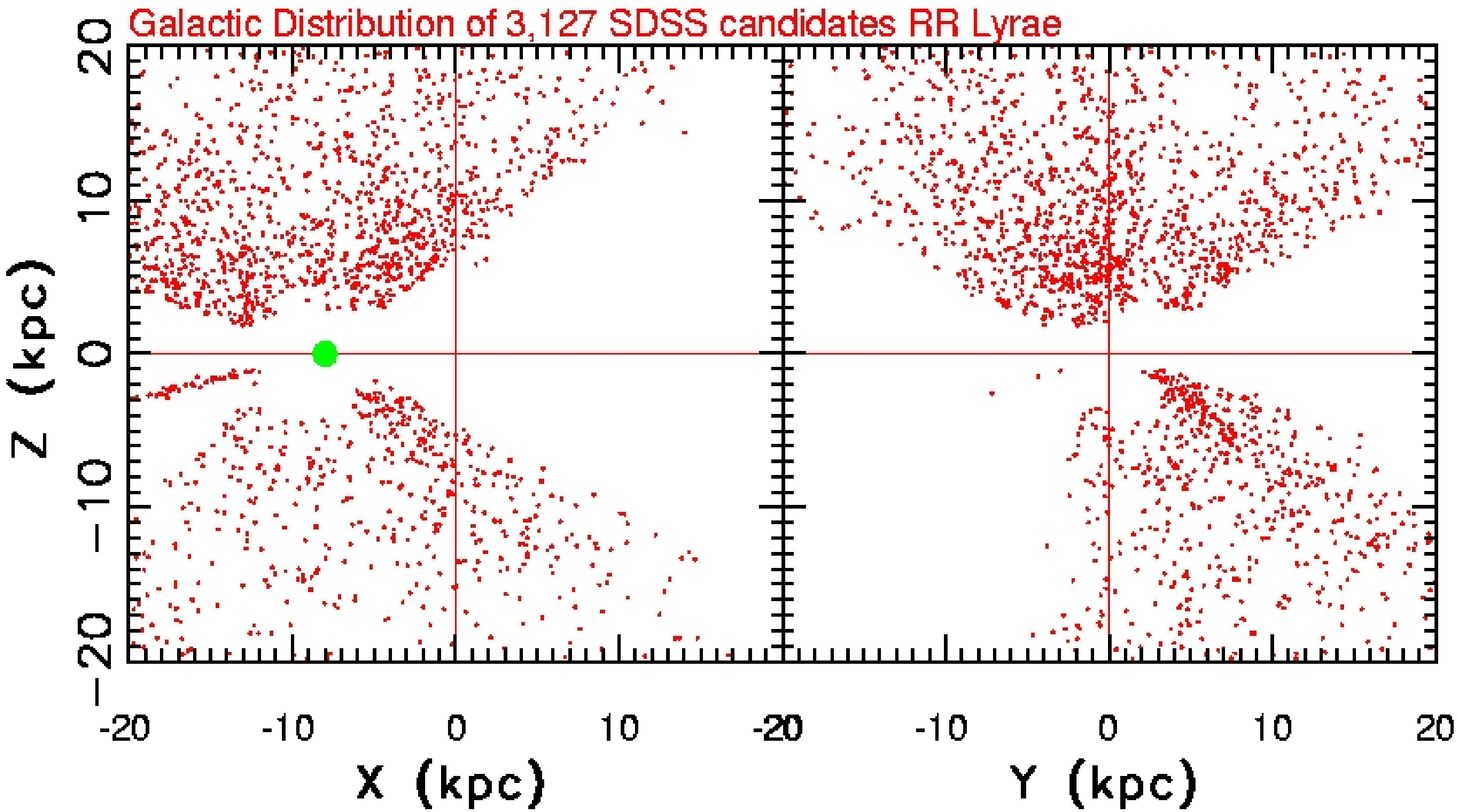
- Distance modulus for 100 kpc is 20 mag – to have an apparent magnitude $m < 21$, a star must have $M < 1$.

- Horizontal branch stars (including RR Lyrae) and red giants are good tracers of the outer halo

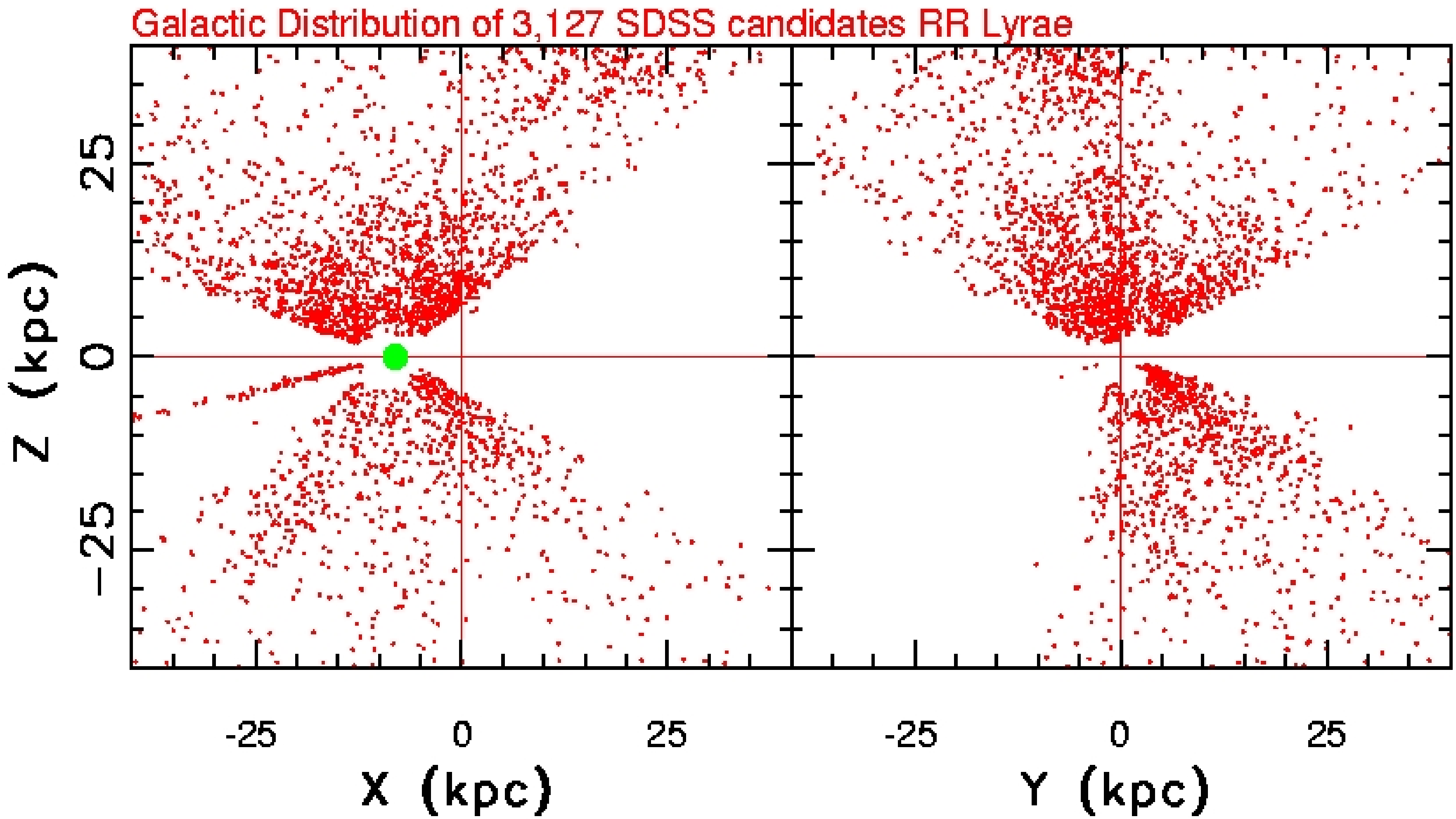
- Selection: RR Lyrae stars: variability, color, spectroscopic selection (?); Horizontal branch stars: color, spectroscopic selection; red giants: color, spectroscopic selection (?)



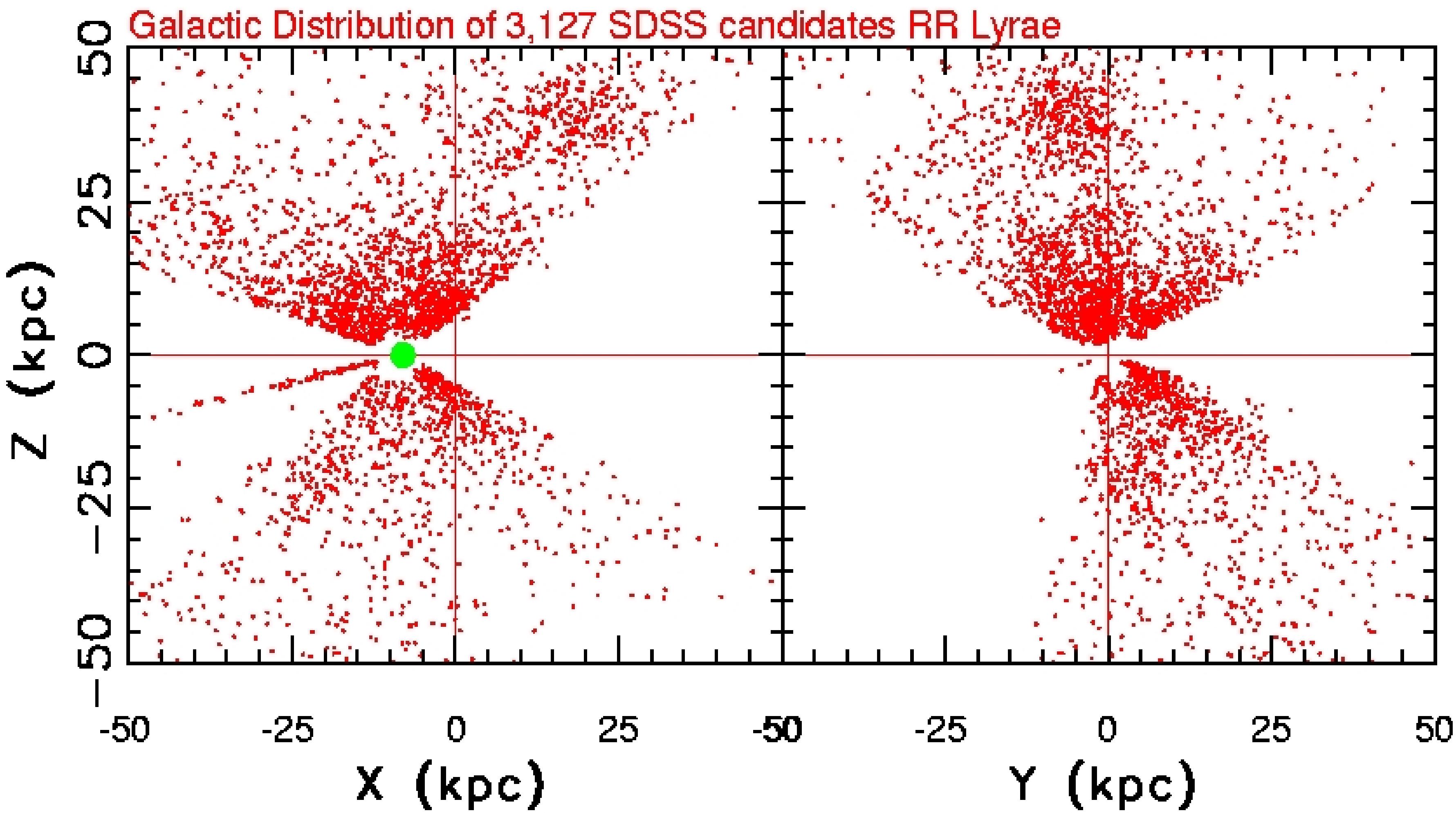
Green dot: Seattle. Red dots: $\sim 3,000$ SDSS RR Lyrae

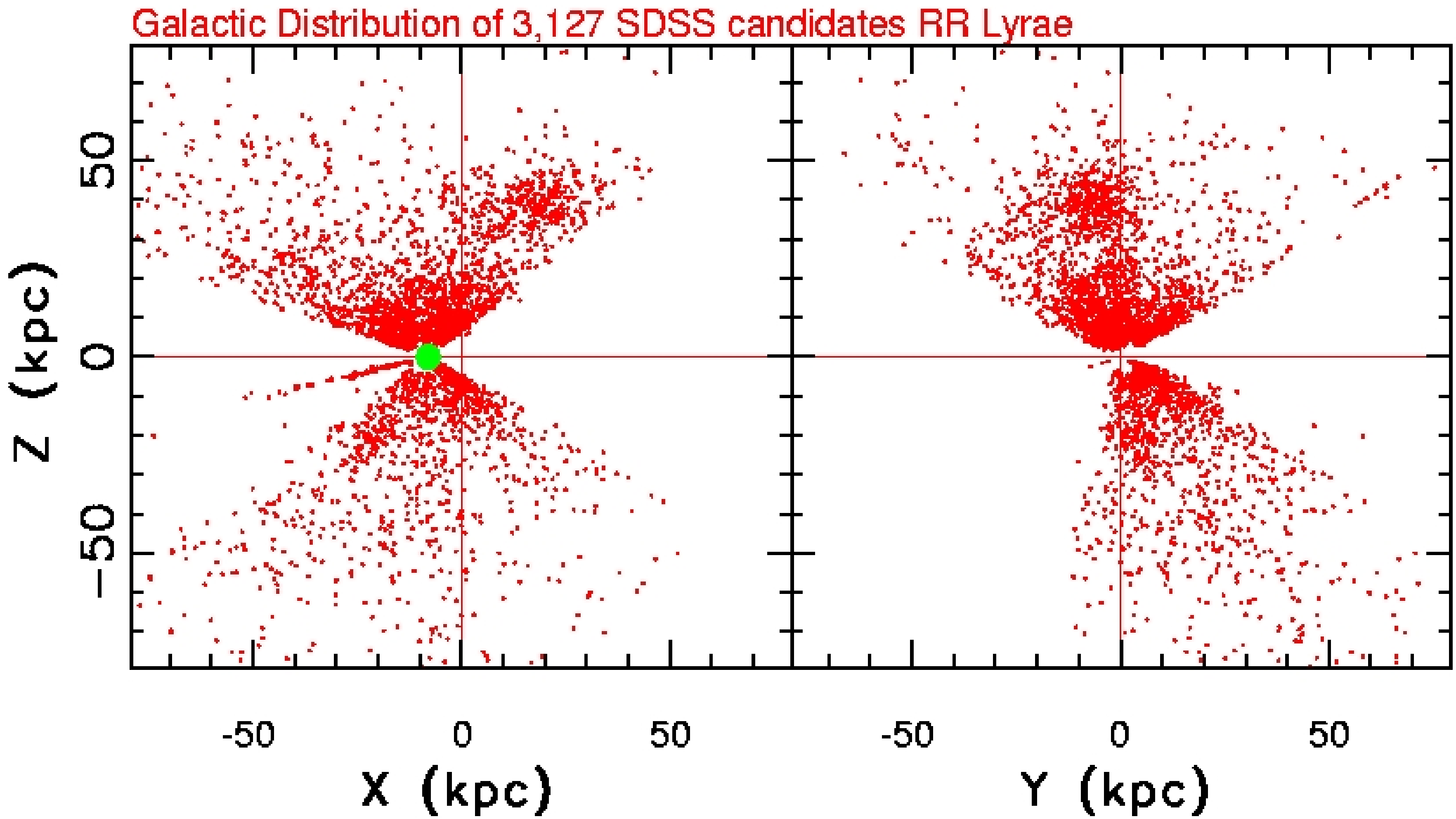


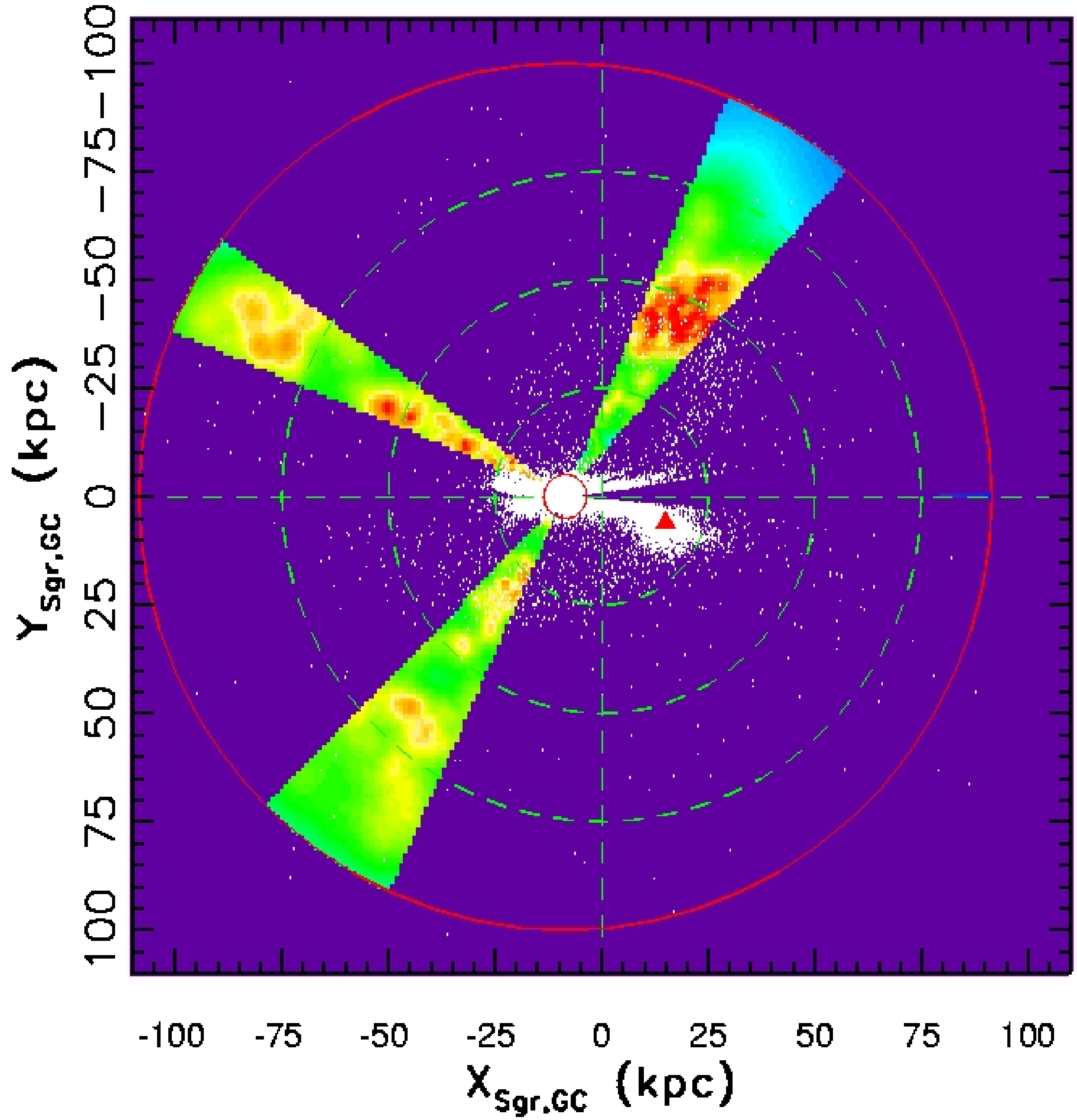
Galactic Distribution of 3,127 SDSS candidates RR Lyrae
Z (kpc)
20
10
0
−10
−20
-20
-10
0
10
-20
-10
0
10
20
X (kpc)
Y (kpc)



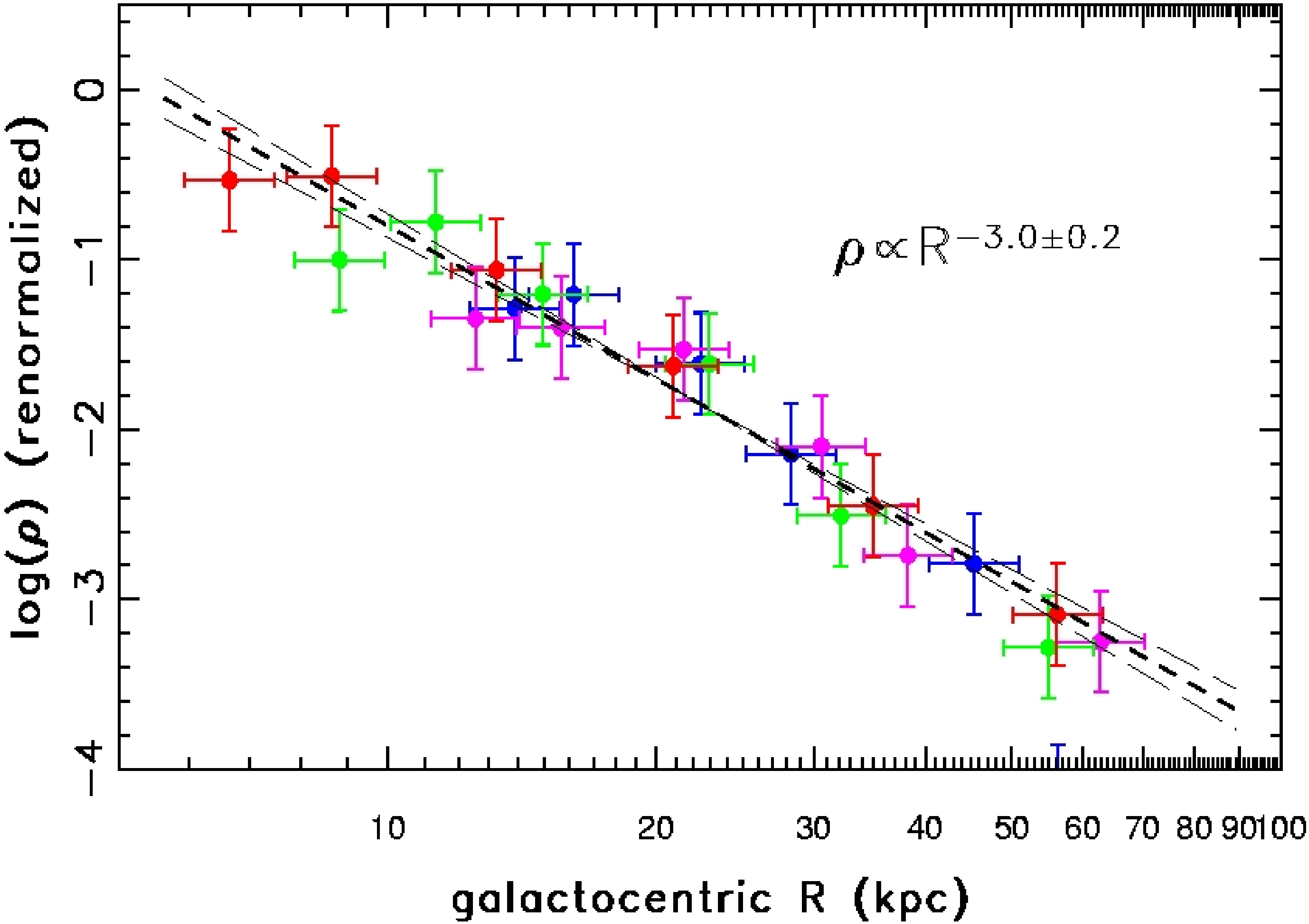
Galactic Distribution of 3,127 SDSS candidates RR Lyrae
Z (kpc)
25
0
−25
-25
0
25
X (kpc)
-25
0
25
Y (kpc)


Galactic Distribution of 3,127 SDSS candidates RR Lyrae
Z (kpc)
X (kpc)
Y (kpc)
50
25
0
−25
−50
-50
-25
0
25
-50
-25
0
25
50


Galactic Distribution of 3,127 SDSS candidates RR Lyrae
Z (kpc)
50
0
−50
-50
0
50
X (kpc)
-50
0
50
Y (kpc)

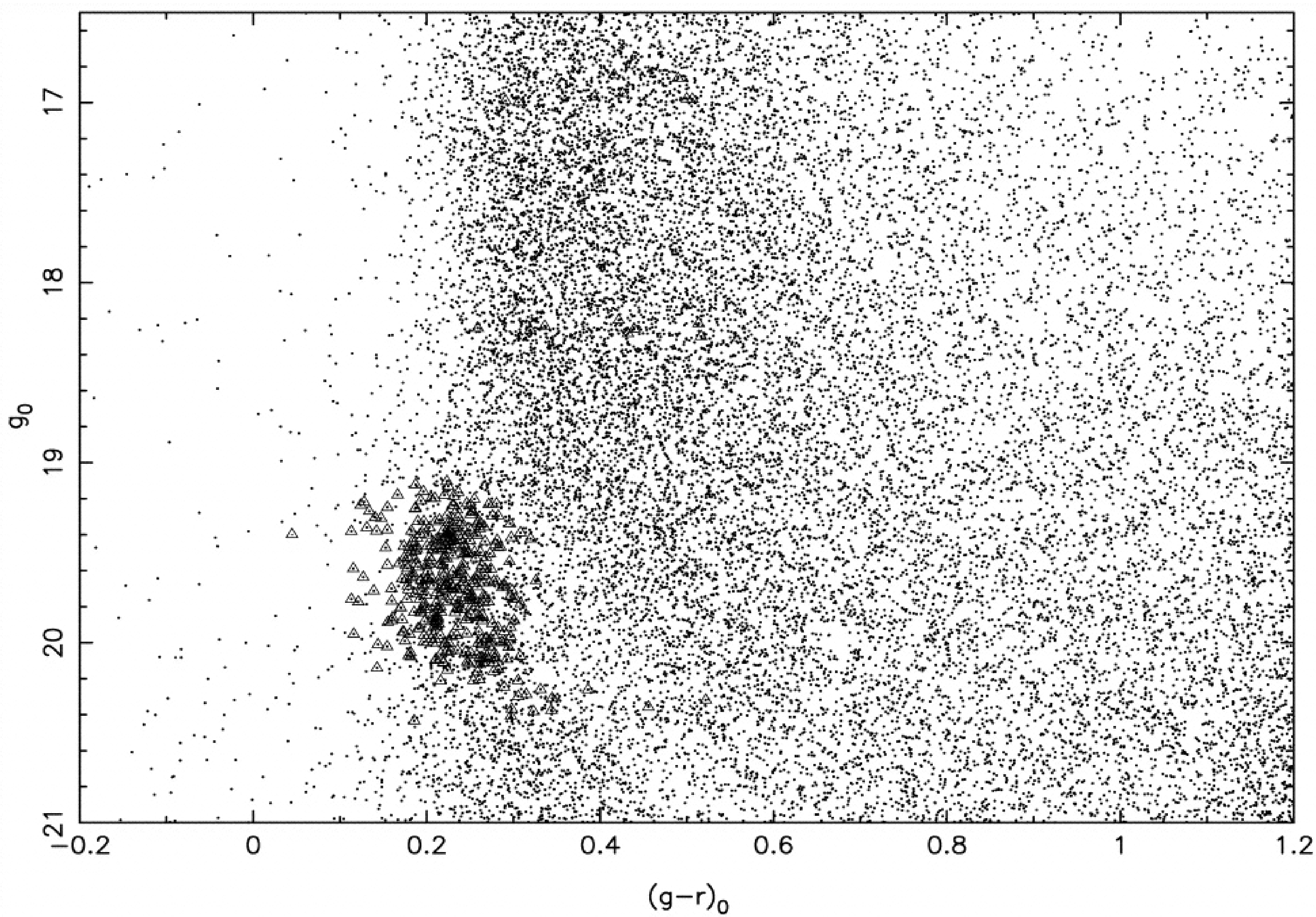


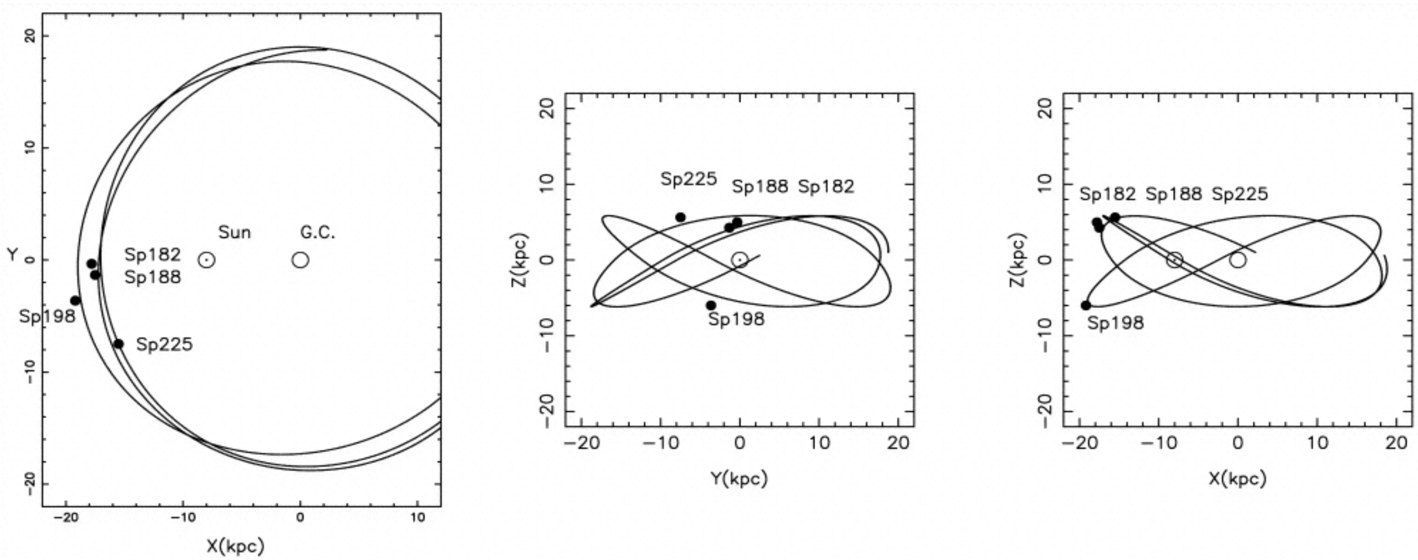
-100 -75 -50 -25 0 25 50 75 100
$X_{Sgr,GC}$ (kpc)
$Y_{Sgr,GC}$ (kpc)
-100 -75 -50 -25 0 25 50 75 100



log(ρ) (renormalized)
0
−1
−2
−3
−4
10
20
30
40
50
60
70
80
90100
galactocentric R (kpc)
ρ ∝ R^{−3.0±0.2}

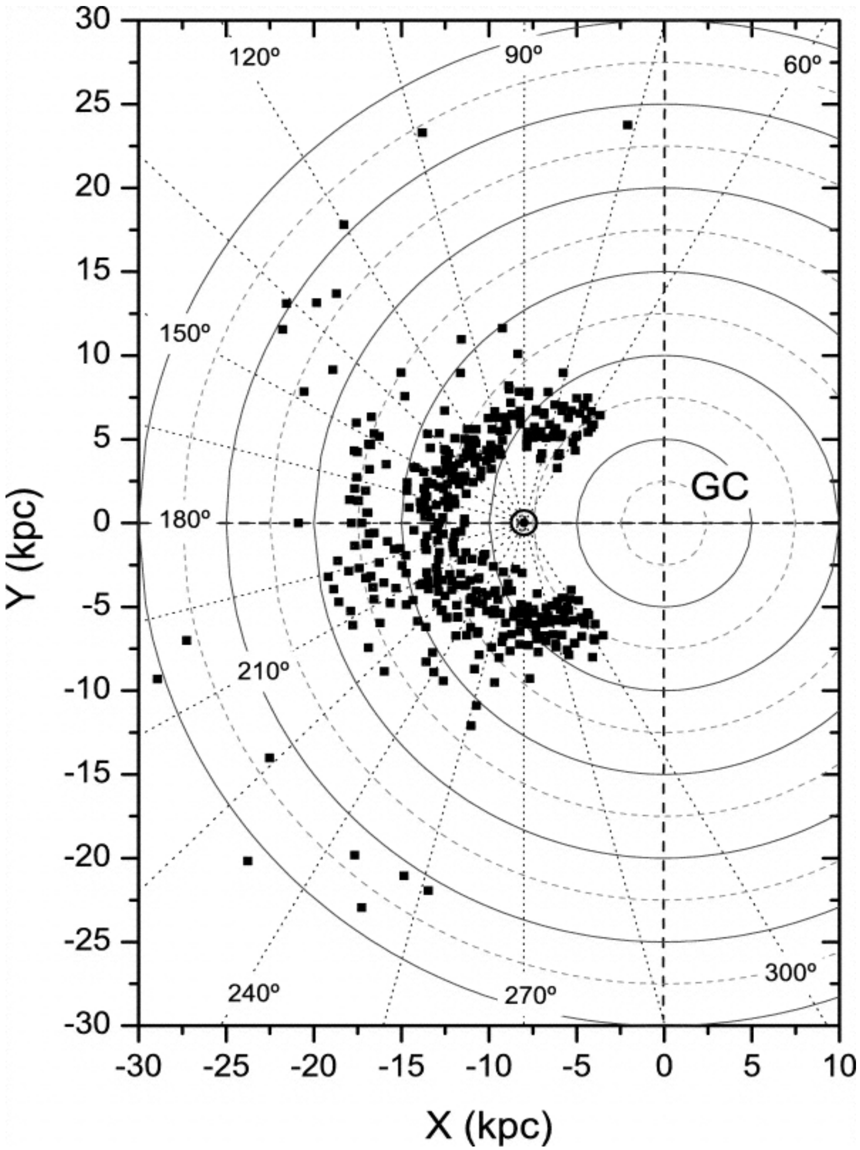
Monoceros "ring" (Yanny et al. 2003)



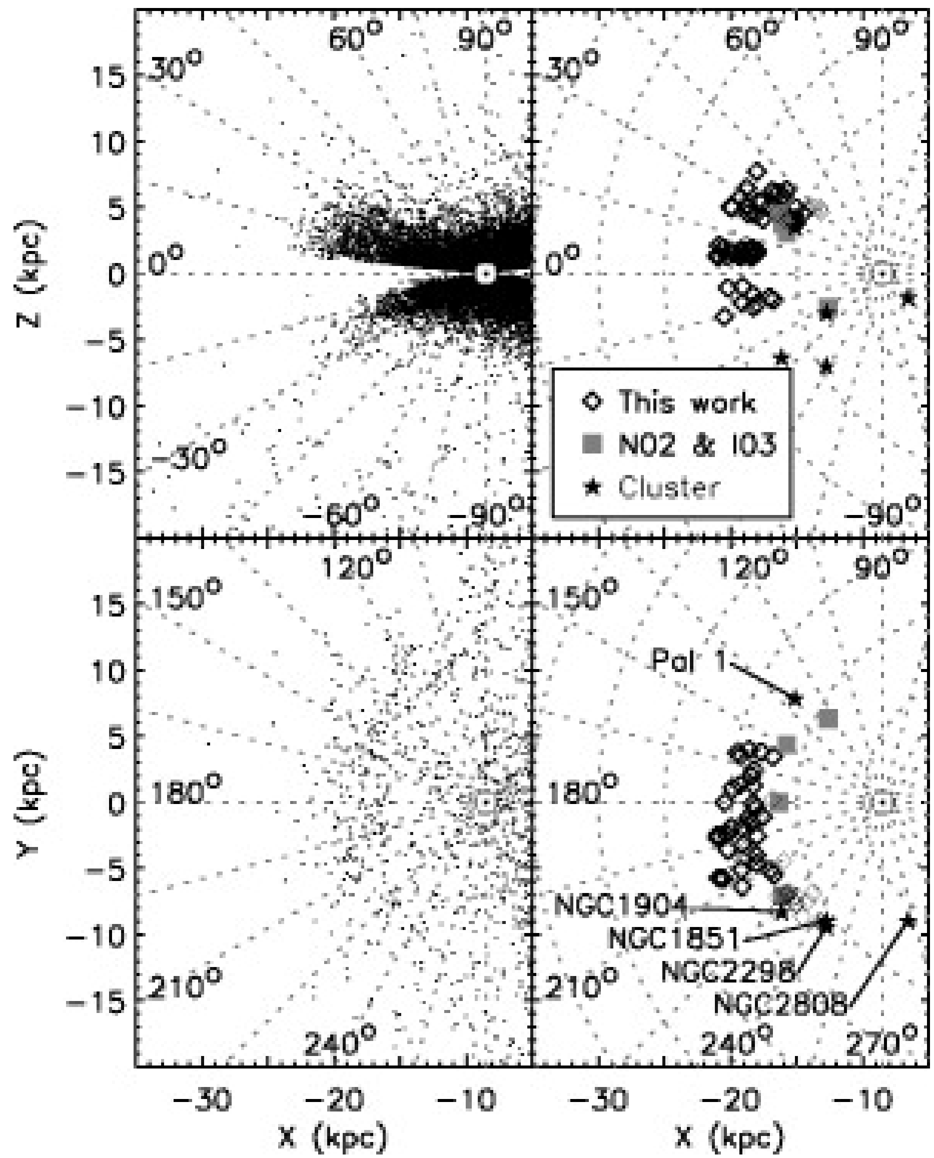


Monoceros "ring" (Yanny et al. 2003)

- consistent with a tidal stream slightly inclined wrt Galactic plane
- confirmed by 2MASS data (Rocha-Pinto et al. 2003, Crane et al. 2003)

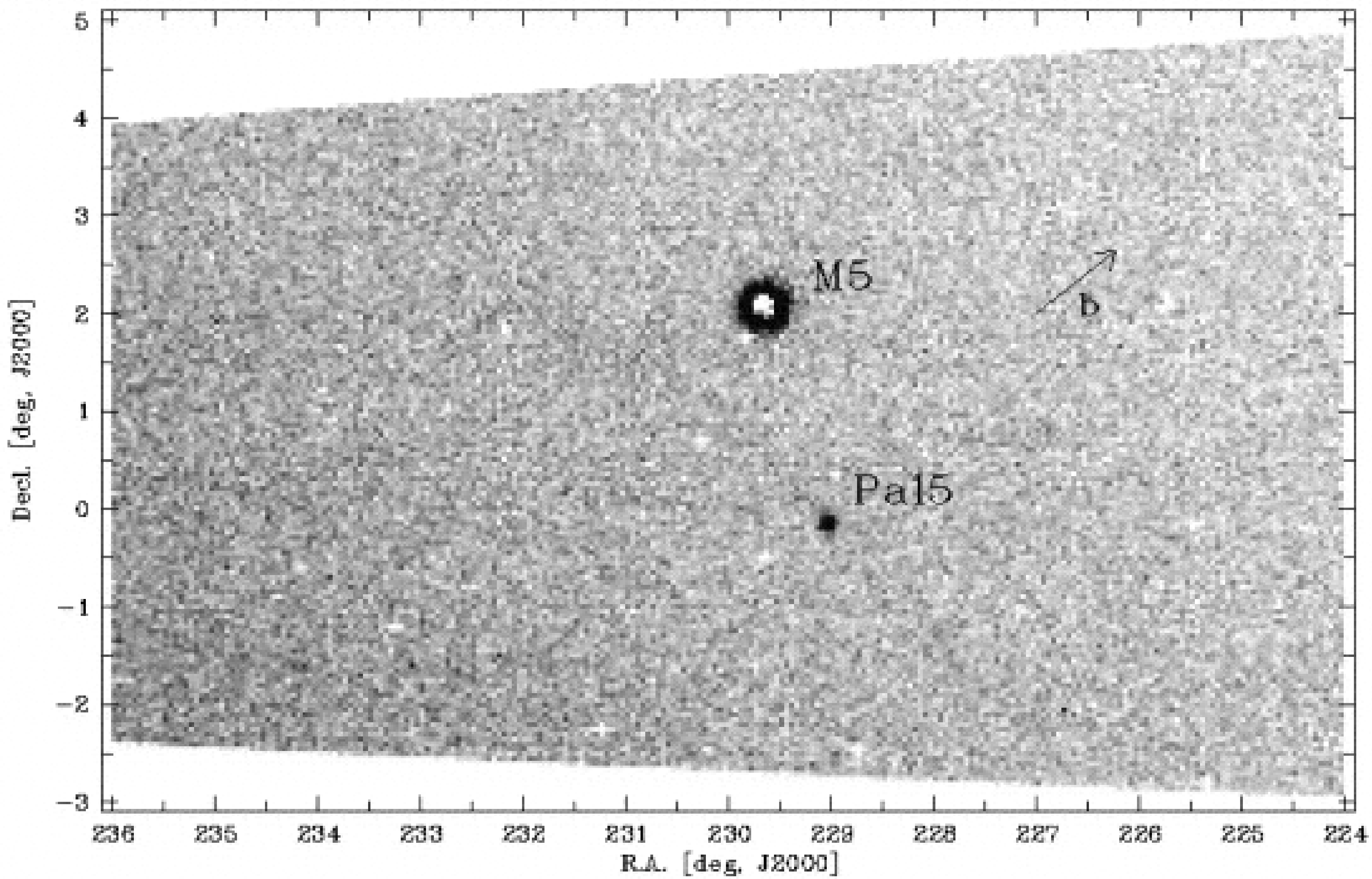


Y (kpc)
X (kpc)
GC
120º
90º
60º
150º
180º
210º
240º
270º
300º

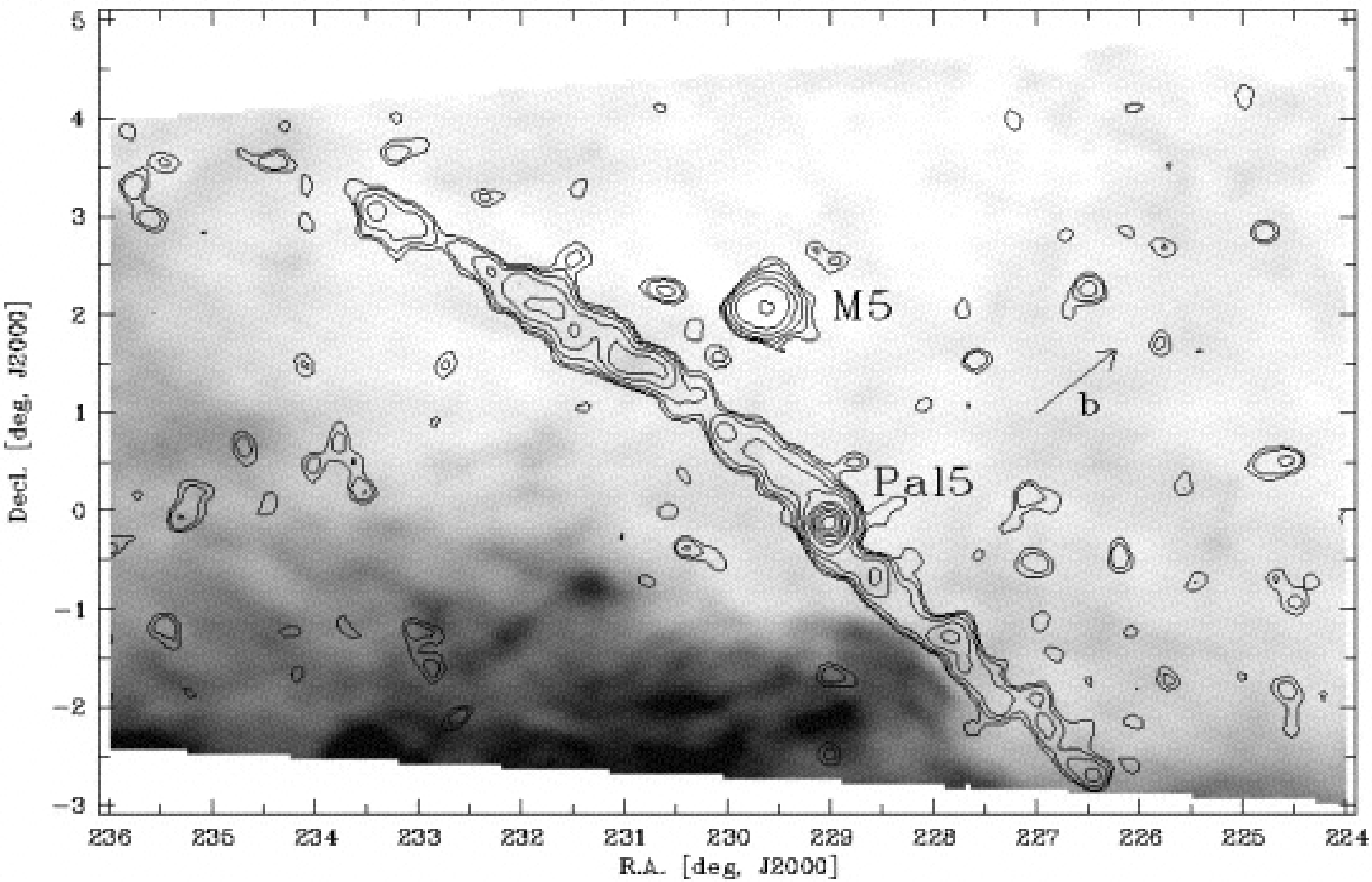


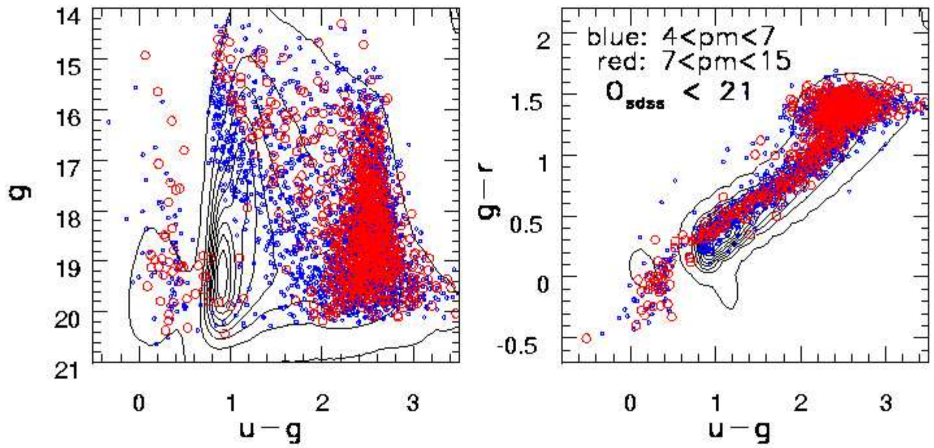
Z (kpc)
Y (kpc)
X (kpc)
This work
N02 & I03
Cluster
Pal 1
NGC1904
NGC1851
NGC2298
NGC2808

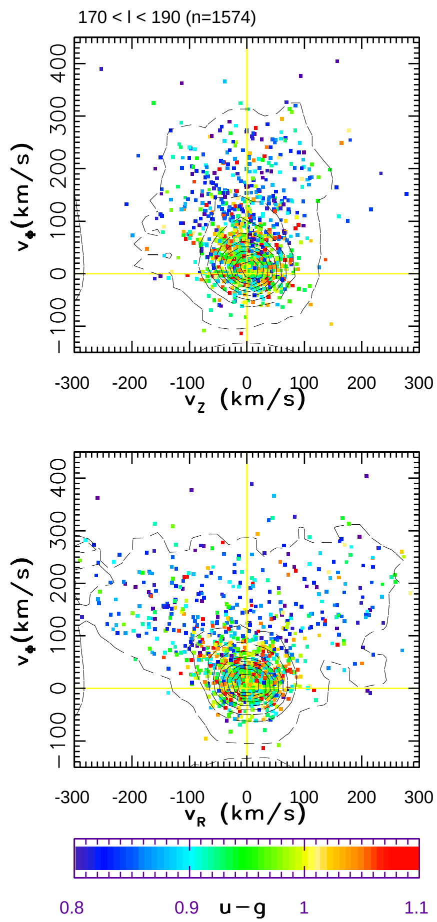
Pal 5 tidal tails (Rockosi et al. 2002, Odenkirchen et al. 2003)



Pal 5 tidal tails: matched filter extraction, gray: SFD E(B-V)



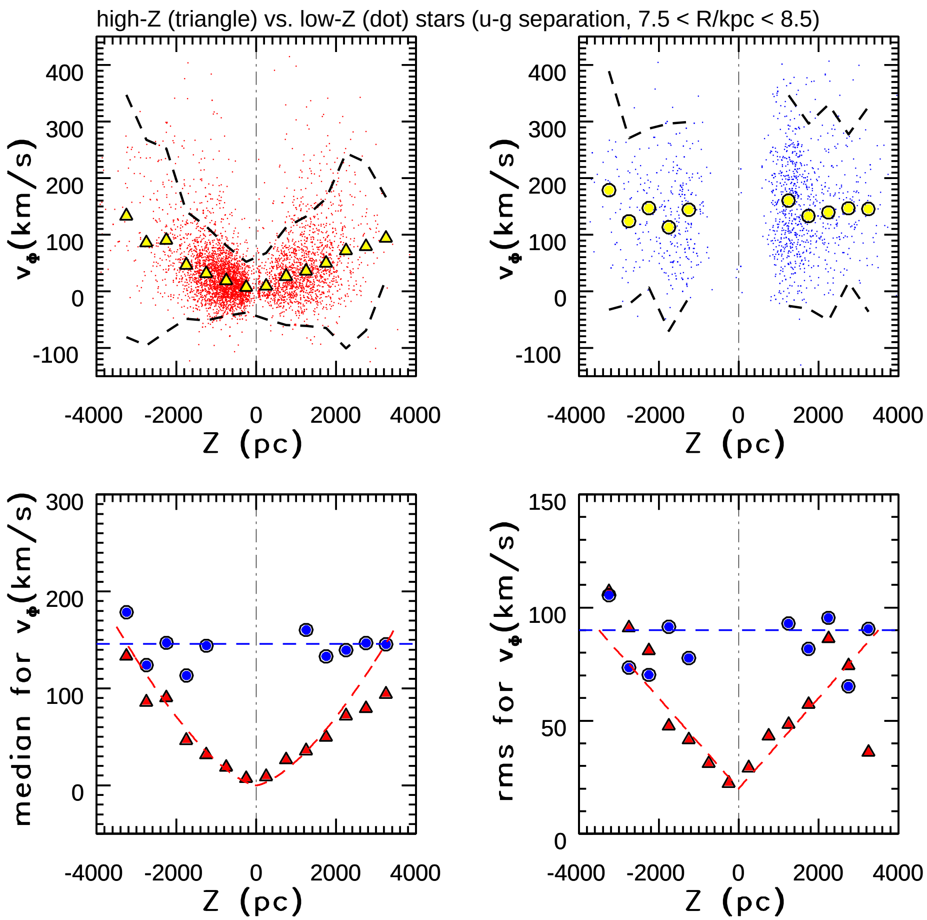




Milky Way Kinematics (with SDSS)

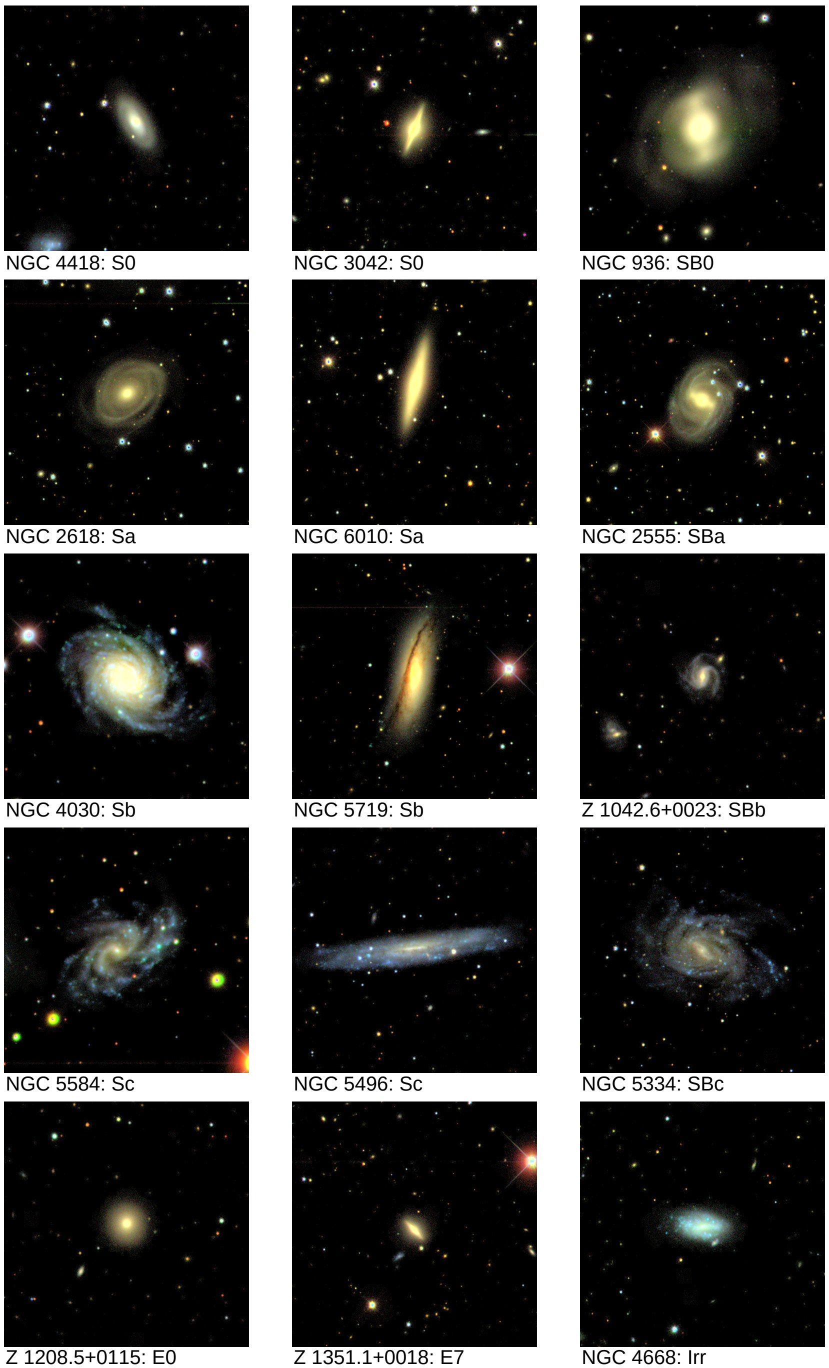
- Kinematics (e.g. proper motions) are a complex function of color and apparent magnitude
- SDSS enables three important advances (accurate distances, radial velocities and proper motions) which results in robust and accurate estimates of all three velocity components
- Data confirm a strong correlation between the kinematics and metallicity (with a 100-1000 large sample than previous studies)

Milky Way Kinematics (with SDSS)



- Both the rotational velocity and the dispersion for all three components appear independent of Z for low-metallicity ($u - g < 1$) stars
- Both the rotational velocity and the dispersion for all three components increase with Z for high-metallicity ($u - g > 1$) stars
- More details in Bond et al. (2005)...

Hubble's Classification of Galaxies



5 arcmin x 5 arcmin true-color g-r-i images from SDSS comissioning data.
Galaxy classification is from SIMBAD.

Zeljko Ivezic and Robert Lupton for the SDSS Collaboration.

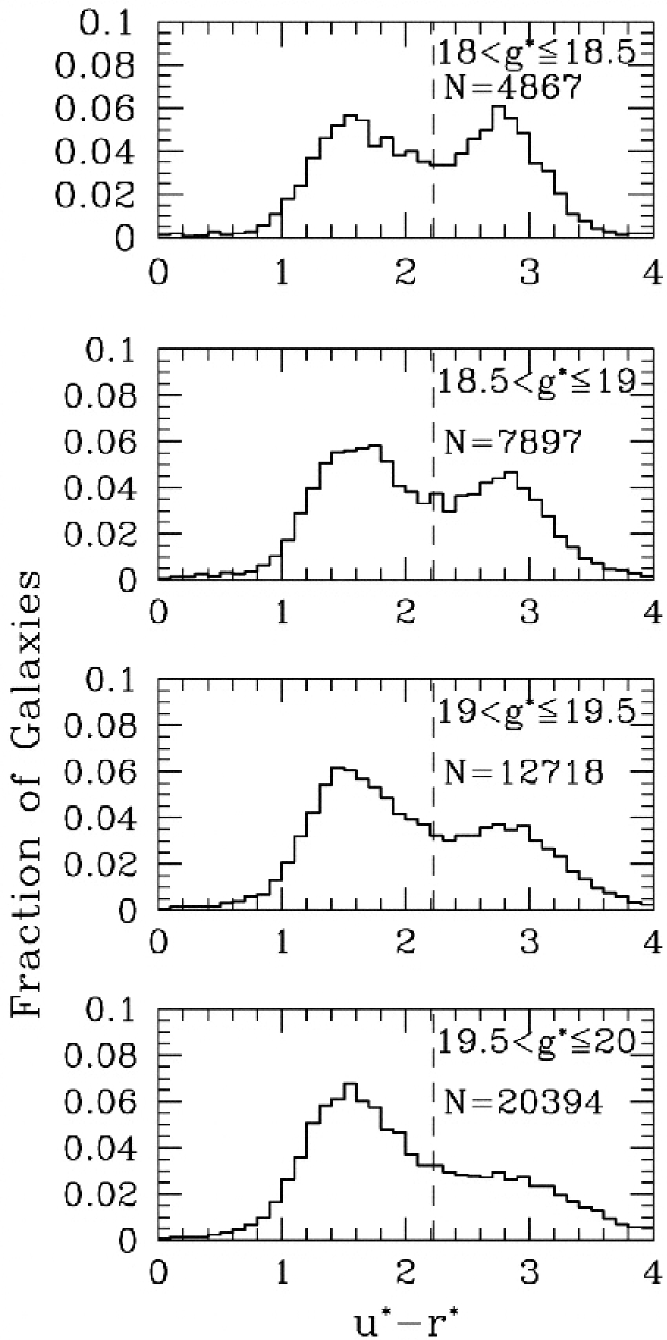
Galaxies (in SDSS)

- Galaxies are (mostly) made of stars (also gas, dust, AGN); hence have similar (but not identical) color distributions
- They come in various shapes (spiral vs. ellipticals; exponential vs. de Vaucouleurs profiles, SDSS concentration parameter)
- Luminosity functions, mass distribution functions, ages, metallicity
- Some host AGNs, some have high star-formation rates
- Nearest neighbors: the Andromeda galaxy (M31), Large and Small Magellanic Clouds, the Sgr Dwarf, Mon stream progenitor (?), the Virgo overdensity (?)

SDSS Spectroscopic Galaxy Survey

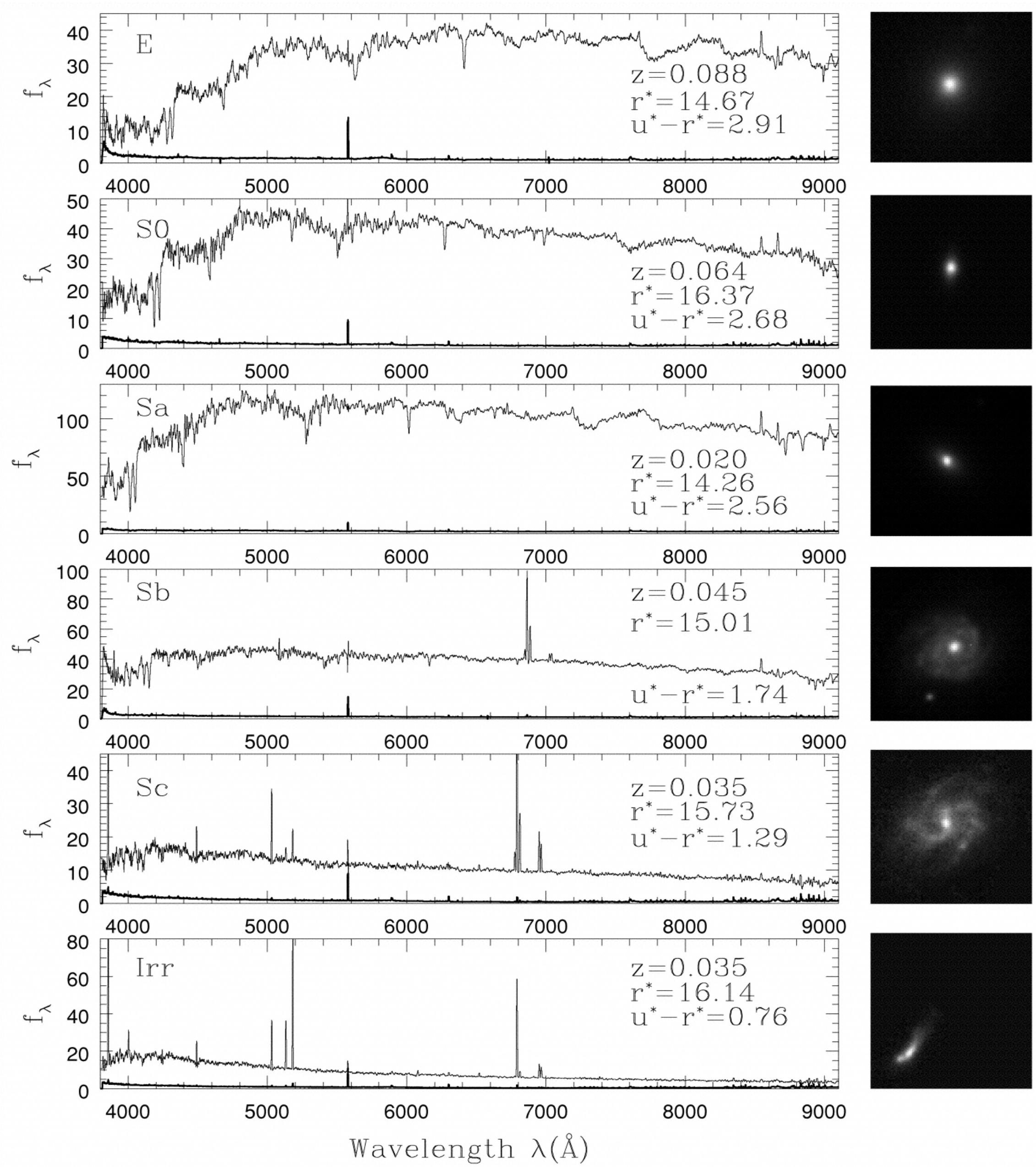
- Two samples: the "main" galaxy sample ($r_{Pet} < 17.77$, Strauss et al. 2002), and luminous red galaxy sample (LRG, cut in color-magnitude space, Eisenstein et al. 2002)

- Distance estimate allows the determination of luminosity function (Blanton et al. 2001)



Bi-modal Color Distribution

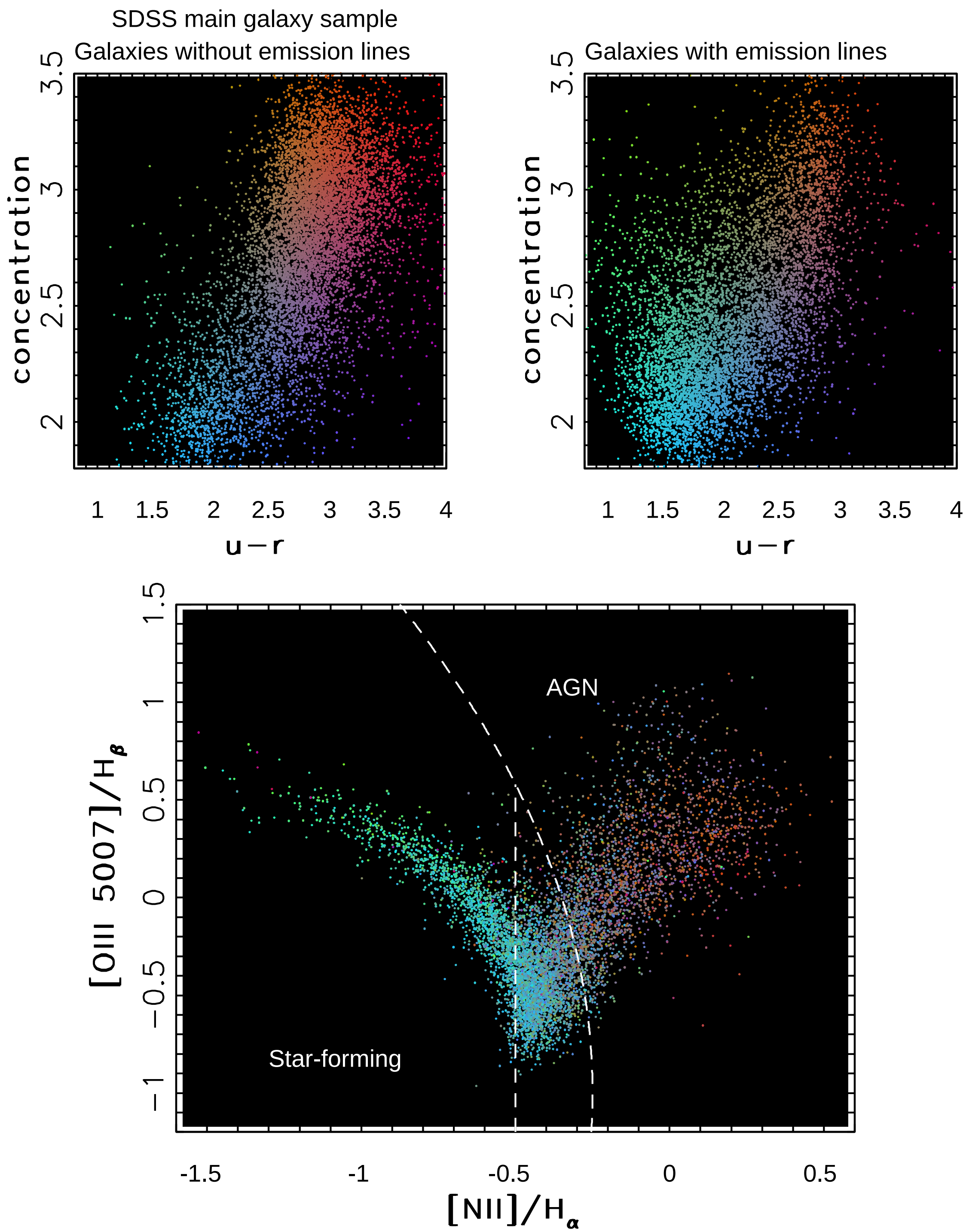
- Strateva et al. (2001): galaxies have bi-modal $u - r$ color distribution
- Colors correlated with shapes and profiles (SDSS concentration parameter)
- **Sersíc index n:** $I(R) \propto \exp(-(R/R_e)^{1/n})$
- $n = 1$: exponential profile
- $n = 4$: de Vaucouleurs profile
- Blanton et al. (2003), Smolčić et al. (2004): "everything is correlated with everything"
- **Schechter function:** $\Phi(L)dL \propto (L/L_*)^\alpha \exp(-L/L_*)\frac{dL}{L}$

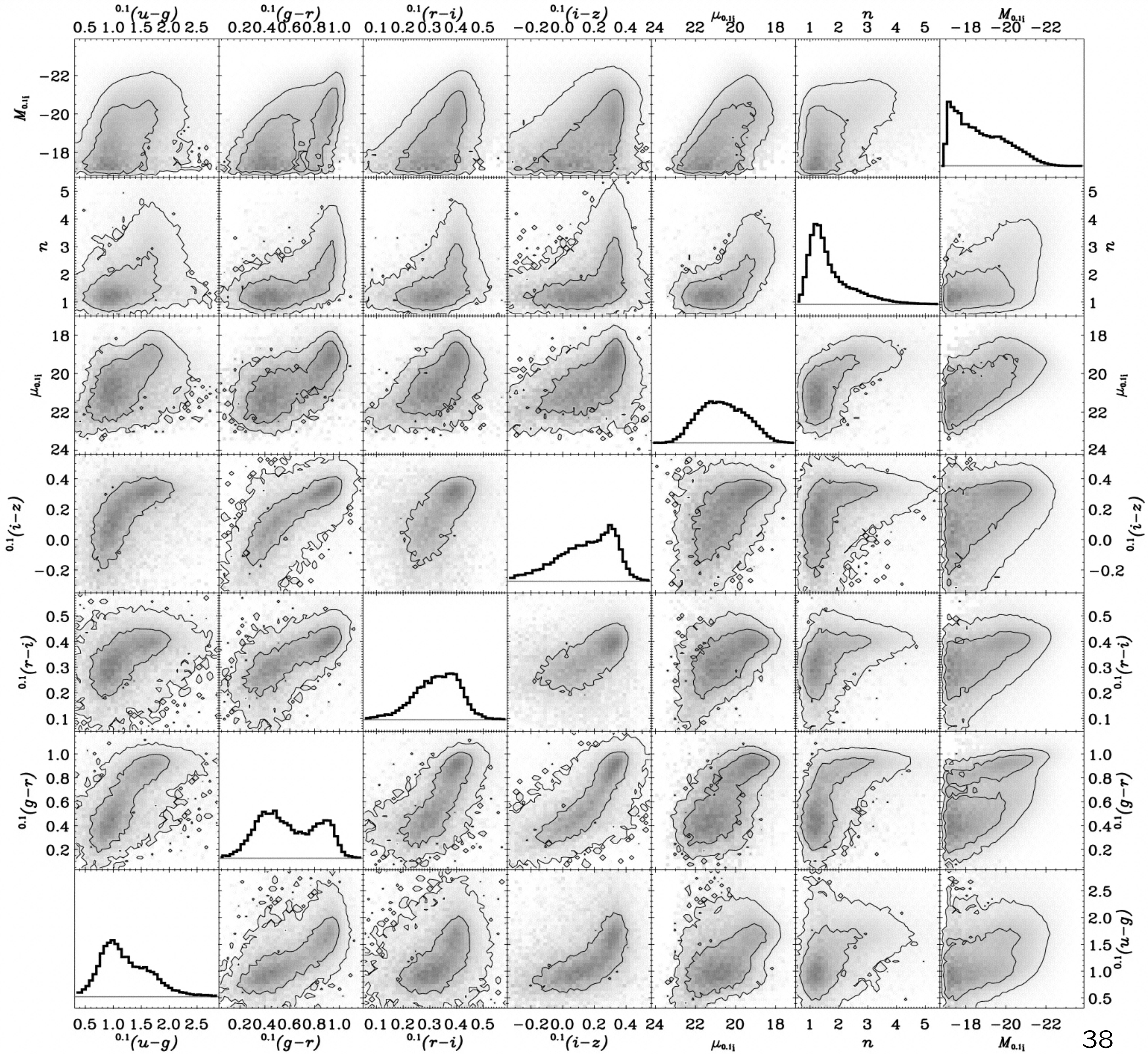


- Spectra are correlated with morphology

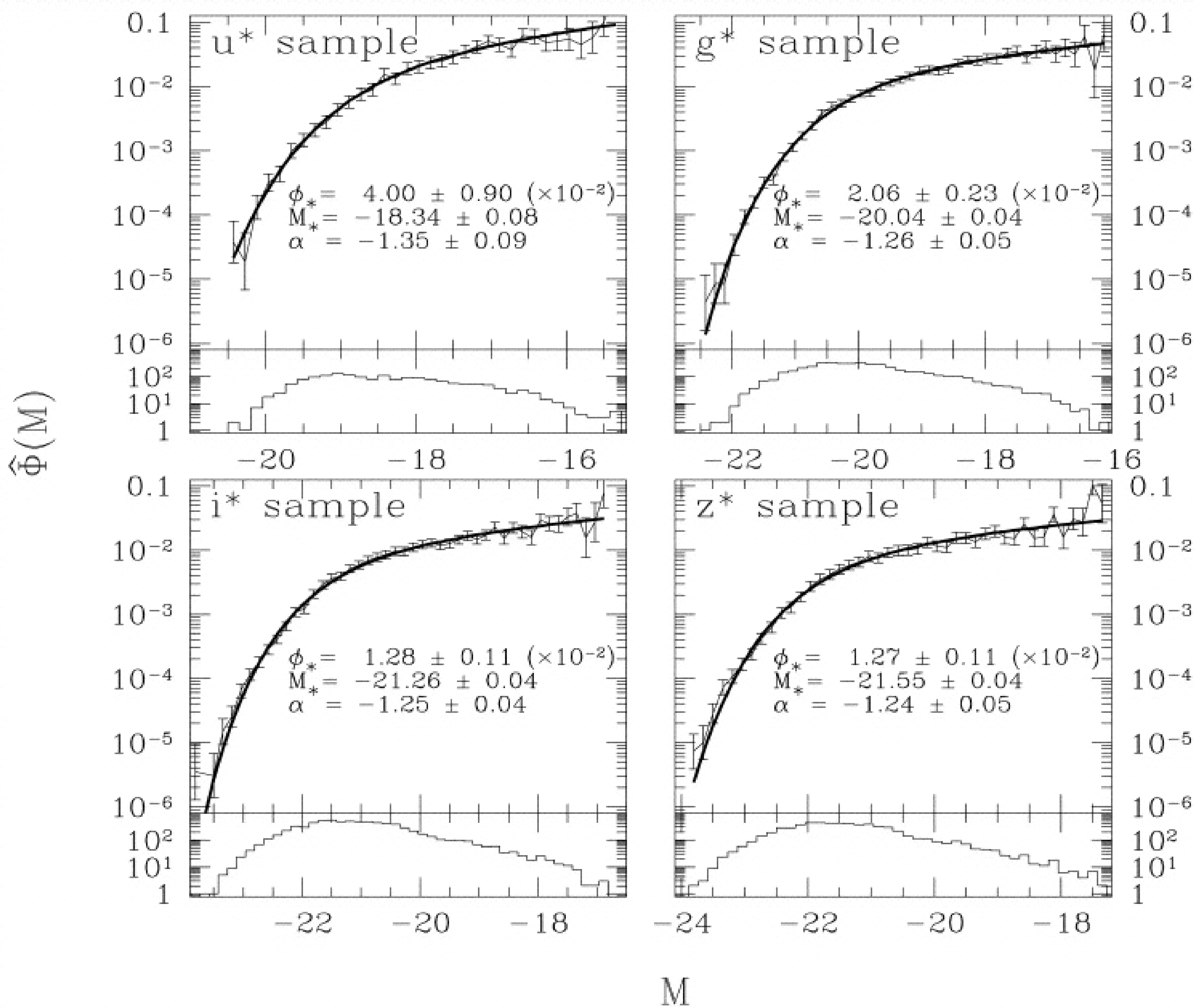
- Principal component analysis: spectra form a low-dimensional family: it is possible to describe most of variance using only 2 parameters (Yip et al. 2004)

- Both AGNs and star-forming galaxies show emission lines: How do we separate AGNs from star-forming galaxies?

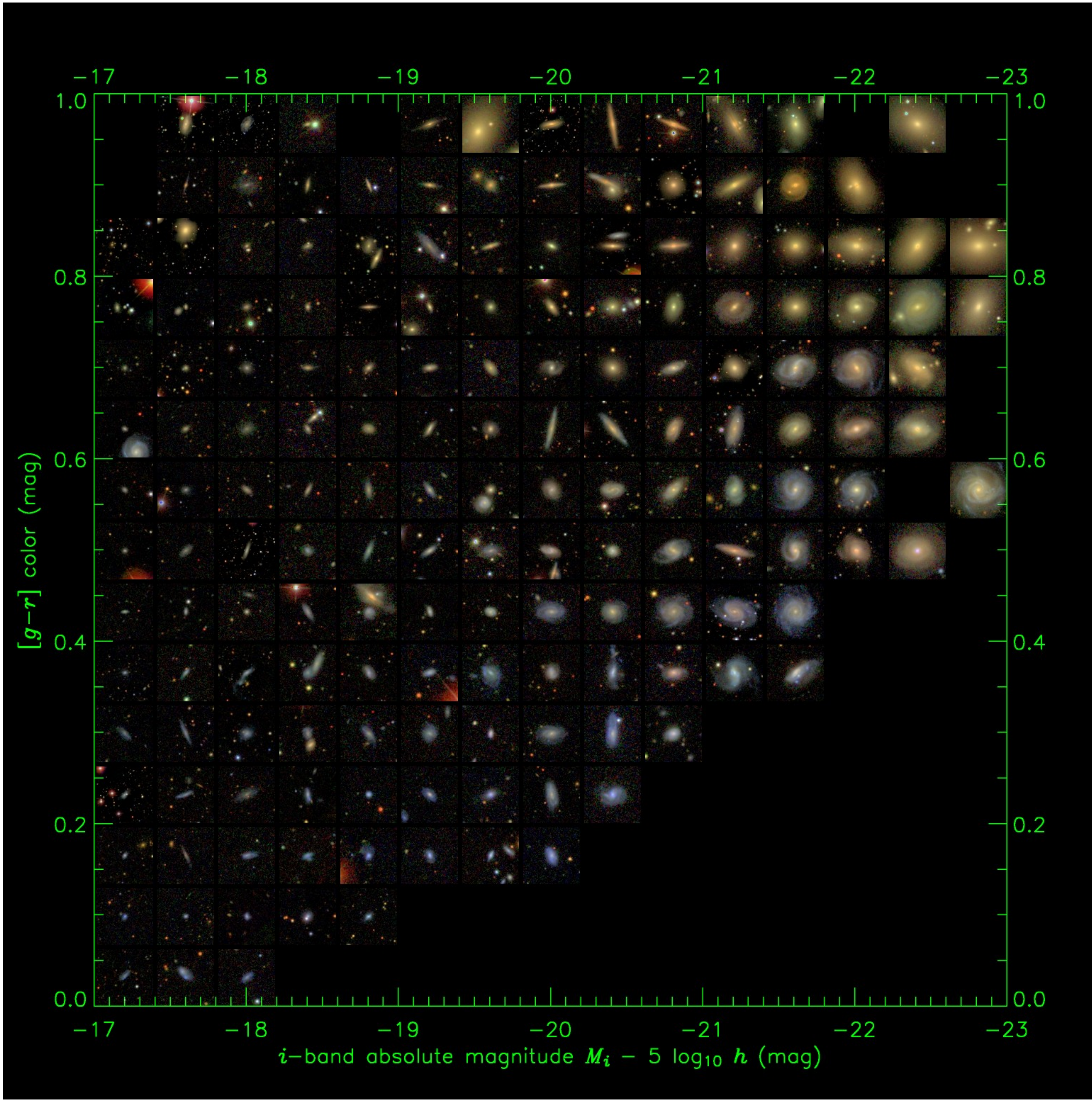

SDSS main galaxy sample
Galaxies without emission lines
Galaxies with emission lines
concentration
u − r
AGN
Star-forming
[OIII 5007]/H$_\beta$
[NII]/H$_\alpha$



0.1(u−g)
0.5 1.0 1.5 2.0 2.5
0.1(g−r)
0.20.40.60.81.0
0.1(r−i)
0.1 0.2 0.3 0.4 0.5
0.1(i−z)
−0.20.0 0.2 0.4
μ0.1i
24 22 20 18
n
1 2 3 4 5
M0.1i
−18 −20 −22
−22 −20 −18
5 4 3 2 1
18 20 22 24
0.4 0.2 0.0 −0.2
0.5 0.4 0.3 0.2 0.1
1.0 0.8 0.6 0.4 0.2
2.5 2.0 1.5 1.0 0.5



u* sample
φ* = 4.00 ± 0.90 (×10⁻²)
M* = −18.34 ± 0.08
α = −1.35 ± 0.09
g* sample
φ* = 2.06 ± 0.23 (×10⁻²)
M* = −20.04 ± 0.04
α = −1.26 ± 0.05
i* sample
φ* = 1.28 ± 0.11 (×10⁻²)
M* = −21.26 ± 0.04
α = −1.25 ± 0.04
z* sample
φ* = 1.27 ± 0.11 (×10⁻²)
M* = −21.55 ± 0.04
α = −1.24 ± 0.05
Φ̂(M)
M



−17
−18
−19
−20
−21
−22
−23
1.0
0.8
0.6
0.4
0.2
0.0
[g−r] color (mag)
i−band absolute magnitude M_i − 5 log10 h (mag)