Galactic disk (sub)structures as revealed by the LSS-GAC value-added catalogue

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Summary

- We report a detailed investigation of the (sub)structure of the Galactic stellar disk, based on two samples selected from the LSS-GAC DR3:
  - A sample containing ~ 0.12 million A stars out to R ~ 14 kpc
  - A sample containing ~ 0.11 million red clump stars out to R ~ 18 kpc

- Based on the A stars, we find:
  - Strong stellar flaring of the Galactic young disk: much stronger than that found by other tracers; Northern disk different from Southern disk
  - Fine substructures: "breathing mode" and "bending mode" perturbations
  - The overdensity of the Perseus Arm

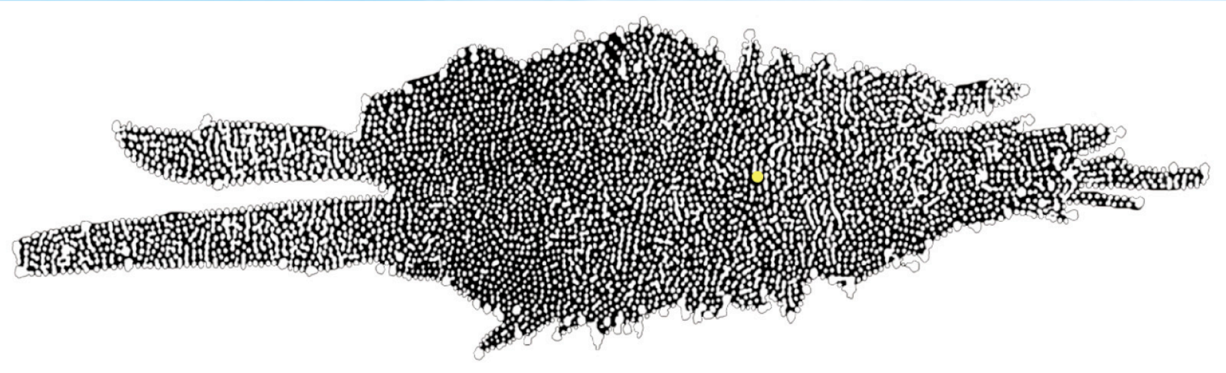
- Based on the RC stars, we find:
  - No truncation until R ~ 18kpc and "waves" like residuals
  - Galactic disk stellar flaring weaker than that traced by the A stars: the stellar flaring correlation with stellar ages

Outline

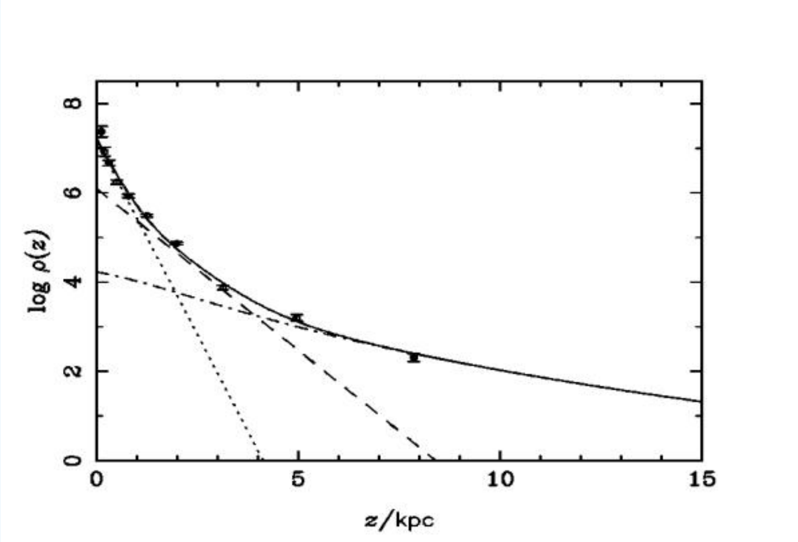
- Introduction
- Data
  - LSS-GAC DR3
  - Sample selection: A stars and RC stars
- Method
- Results
  - Stellar number density maps of A stars
  - Stellar number density maps of RC stars
- Summary

Introduction

- Our position within the Milky Way (MW) Galaxy makes studying its structure and evolution both uniquely challenging and rewarding. Early in the 18th century, the famous astronomer William Herschel was able to tell that the Galaxy is a disk (Herschel 1785).



- The standard Galactic model is established until 1980s



- Bahcall & Soneira (1980): two components of the Galactic model, namely disc and halo.
- Gilmore & Reid (1983): improved the model by introducing a third component, namely the thick disc.
- The Galactic disk(s) usually described as smooth exponential component(s)

$$\rho_D(R, Z; L, H) = \rho_D(R_\odot, 0) e^{R_\odot/L} \exp\left(-\frac{R}{L} - \frac{Z + Z_\odot}{H}\right)$$

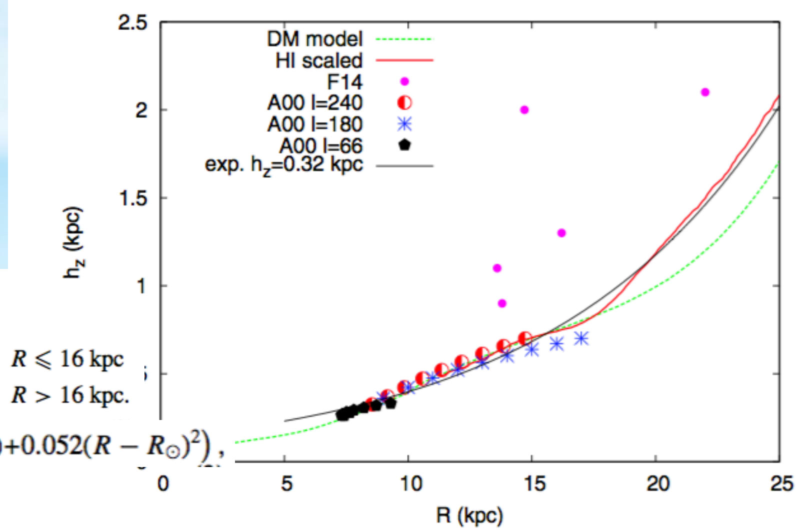
Introduction

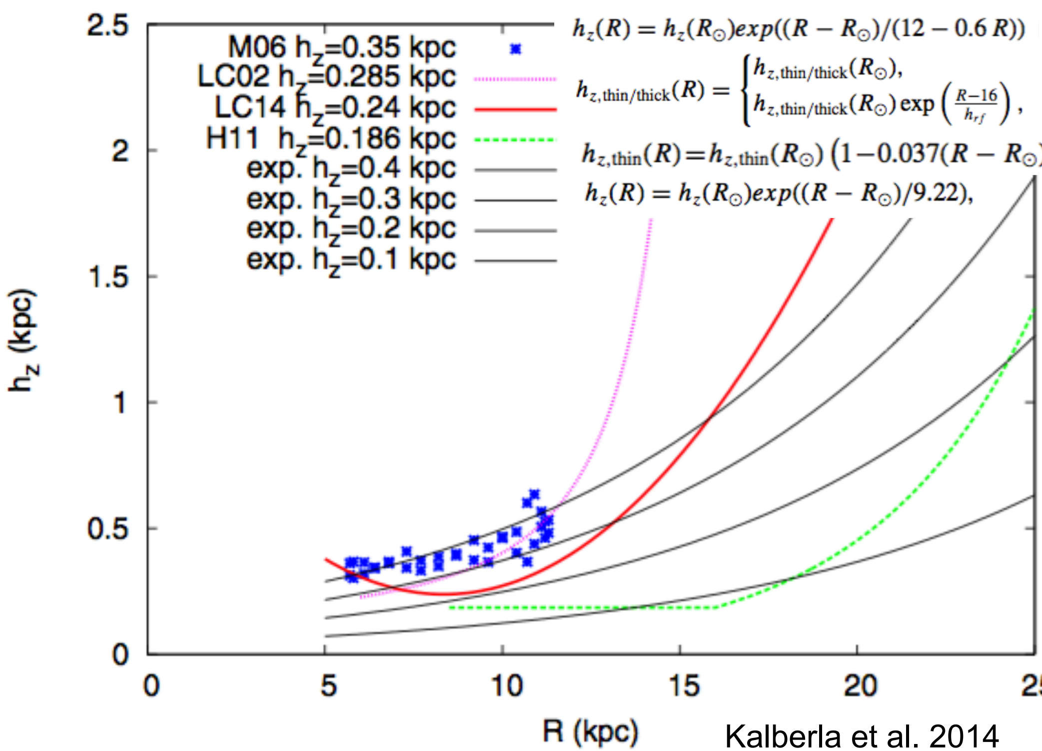
- The constituent components of the MW can be observed in unique detail. However, disentangling its structure is complicated by difficulties in
  - obtaining accurate distances to objects
  - and frequently heavy extinction.

- Studying the Galactic thin disc is particularly difficult, within the thin disc,
  - extinction is at its strongest
  - and its constituent stellar population is a smooth mix of stars formed over a wide range of ages, in vastly differing conditions and locations, and which migrate across the Galaxy. *Such difficulties help to explain the vast range of results which have been obtained when determining parameters such as the scale-length and scale-height of the stellar density in the thin disc (Chen et al. 2017a*)
- The MW is often approximately considered to be steady and axisymmetric. In such a model, disk stars are expected to have quite smooth and simple distributions. This simple picture is, however, challenged by the recent studies.

Galactic disk stellar flaring

- HI gas in the MW shown early on the h_Z increases with R (Lozinskaya & Kardashev 1963). Whether the stellar populations in the MW flares as HI? Standard mass models for the MW assume a constant scale height (Robin et al. 2003; Girardi et al. 2012; Sharma & Bland-Hawthorn 2013).
- Recently works: at least some of the stellar distributions, at large R, high altitudes, are incompatible with a constant scale height.
- Is there a common Flaring Model for Stars?





$$h_z(R) = h_z(R_\odot)exp((R - R_\odot)/(12 - 0.6\,R))$$

$$h_{z,\mathrm{thin/thick}}(R) = \begin{cases} h_{z,\mathrm{thin/thick}}(R_\odot), & R \leqslant 16 \text{ kpc} \\ h_{z,\mathrm{thin/thick}}(R_\odot)\exp\left(\frac{R-16}{h_{rf}}\right), & R > 16 \text{ kpc.} \end{cases}$$

$$h_{z,\mathrm{thin}}(R) = h_{z,\mathrm{thin}}(R_\odot)\left(1-0.037(R-R_\odot)+0.052(R-R_\odot)^2\right),$$

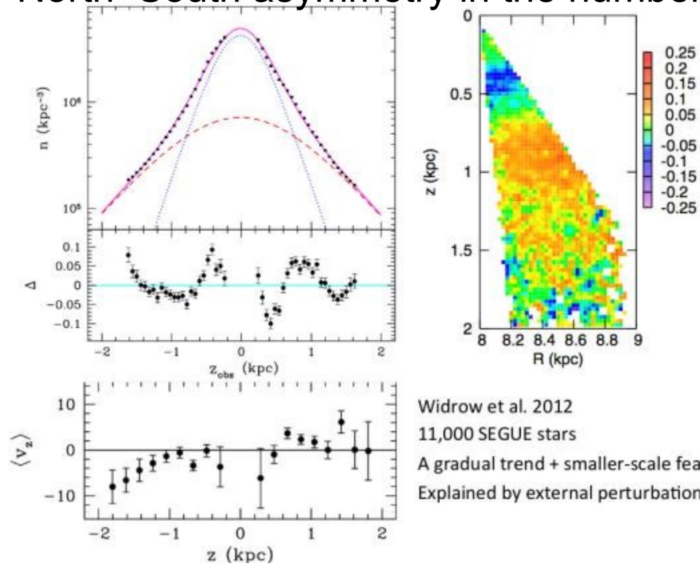
$$h_z(R) = h_z(R_\odot)exp((R - R_\odot)/9.22),$$

Kalberla et al. 2014

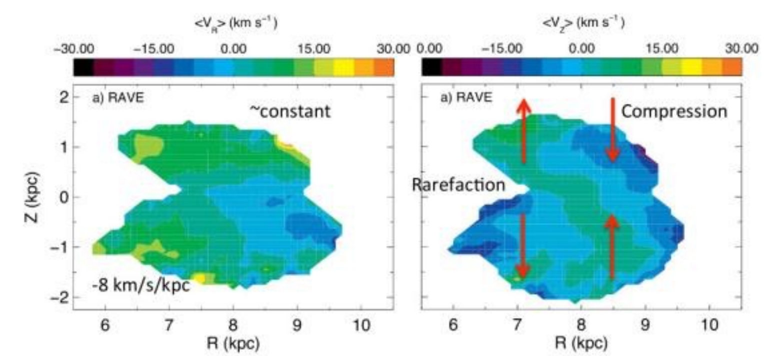
- Alard (2000): the first to report on evidence for the flaring of stars based on the 2MASS data, but his contribution remains unpublished.
- Lopez-Corredoira et al. (2002, LC02): RC stars and old disk stars from 2MASS.
- Hammersley & Lopez-Corredoira (2011, H11): F8V to G5V stars from SDSS DR7.
- Lopez-Corredoira & Molgo (2014, LC14): F8V-G5V stars from SEGUE

North-South Asymmetry

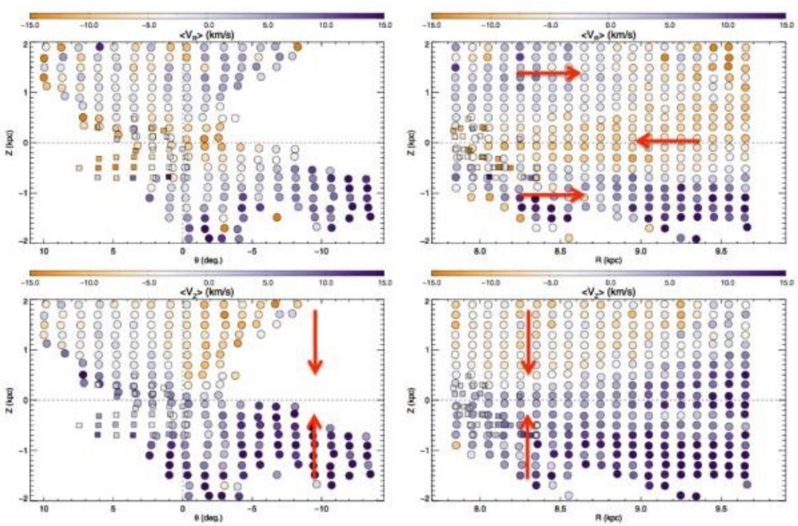
Recent surveys (SDSS, RAVE, APOGEE, LAMOST) have revealed evidence for a Galactic North–South asymmetry in the number density and bulk velocity of solar neighborhood stars.



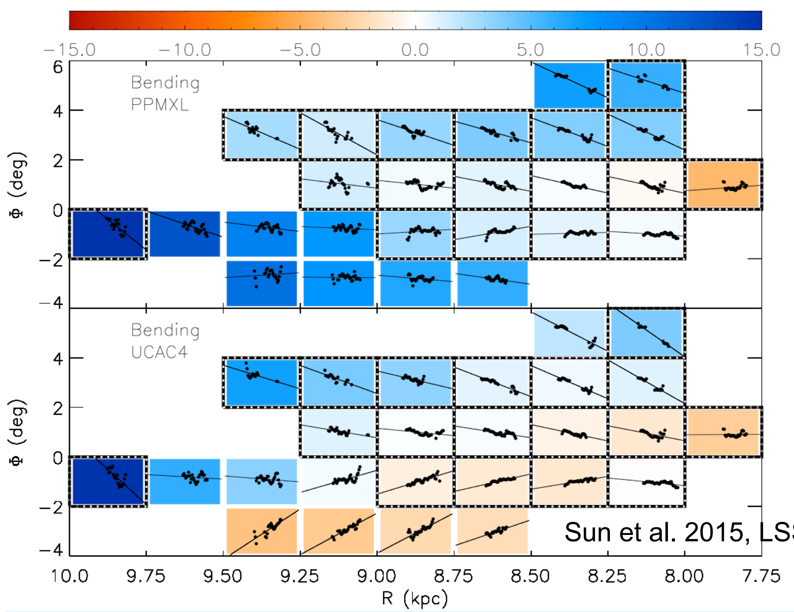
Widrow et al. 2012
11,000 SEGUE stars
A gradual trend + smaller-scale features
Explained by external perturbations



Williams et al., 2013
72,365 RAVE red clumps



Carlin et al. 2013 380, 159 LAMOST F-type stars

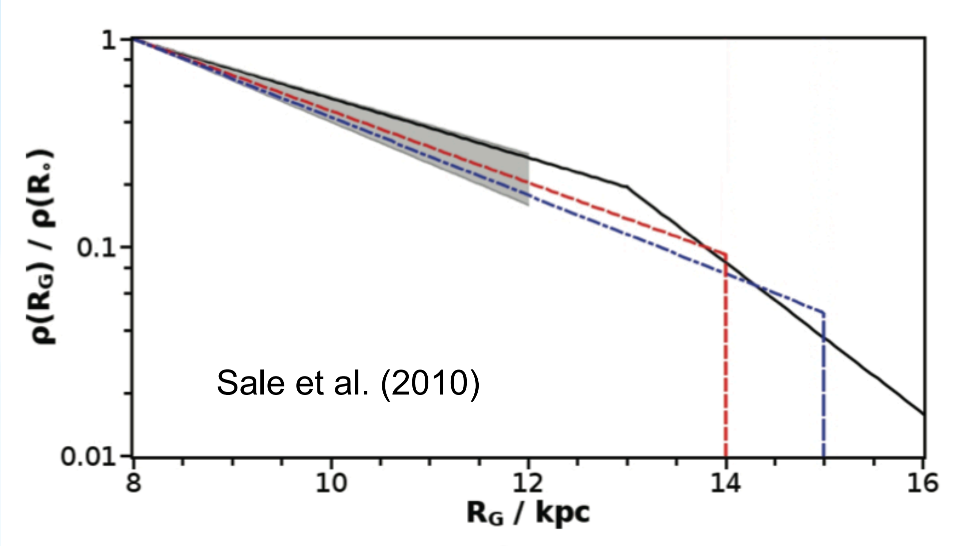


Sun et al. 2015, LSS-GAC DR2

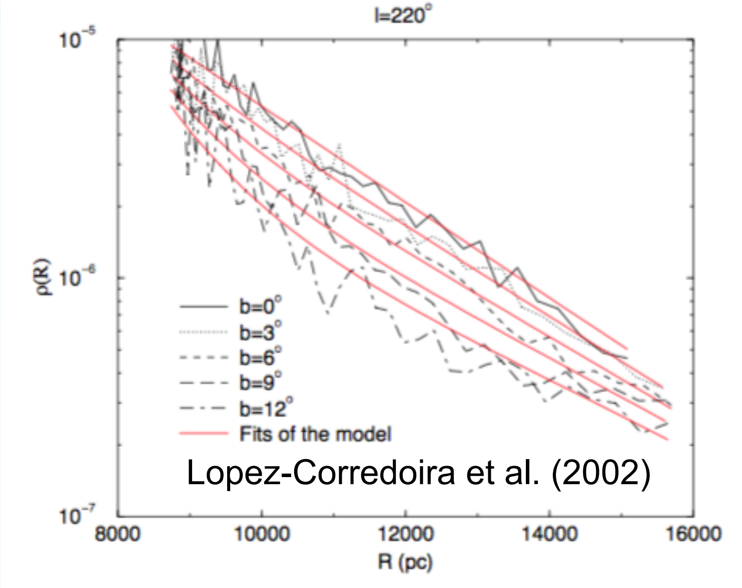
Can we see these (fine)structures from the stellar distribution?

Truncations

- The disc truncation has been often observed in external galaxies: Kregel et al. (2002) finds that 60% of the spiral galaxies are truncated.



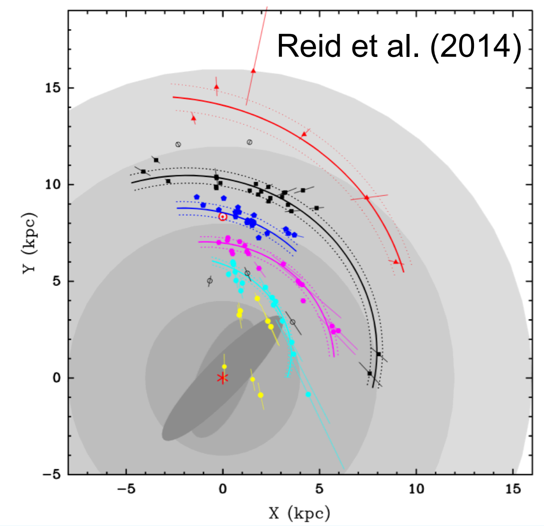
- Habing (1988): OH/IR stars; R_T=14-15 kpc
- Robin et al. (1992a): UBV photometry; R_T=14 kpc
- Ruphy et al. (1996): DENIS data; R_T=15 kpc
- Sale et al. (2010): IPHAS A stars; R_T=13 kpc
- Amores et al. (2017): 2MASS data; R_T=16 kpc



- Lopez-Corredoira et al. (2002): 2MASS red clumps; did not find a disc truncation at distances closer than 20 kpc
- Lopez-Corredoira et al. (2014): SDSS F8V-G5V dwarfs; no truncation or abrupt fall-off for *R* ~ 30 kpc

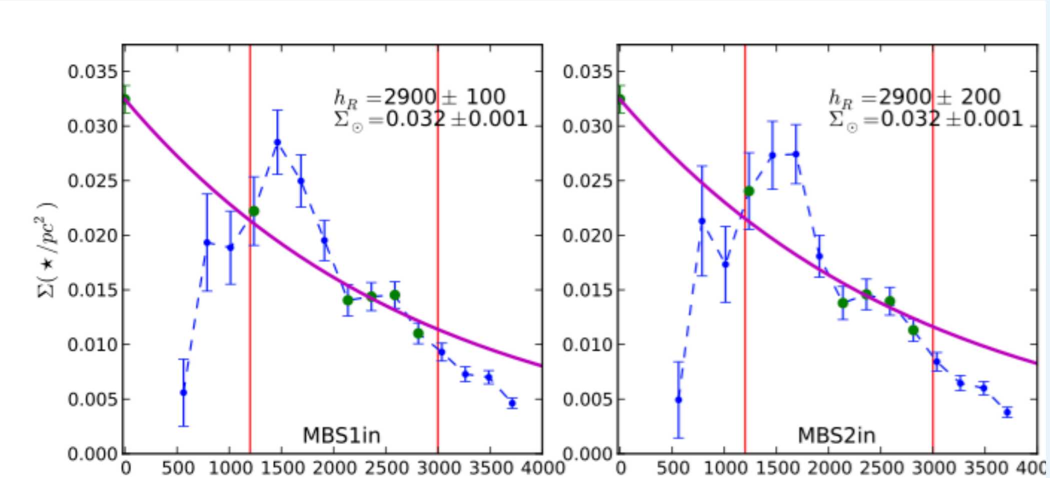
The Perseus Arm

- The spiral arm structure in the Galactic disk is an important component when studying the morphology and dynamics of the Milky Way. However, we still lack a complete picture that describes the nature, origin, and evolution of this structure.
- The Perseus spiral arm, with its outer structure placed near the Sun, is an excellent platform from which to undertake a study of its nature.



- HI neutral gas (Lindblad 1967);
- large-scale CO surveys (Dame et al. 2001); a compilation of open clusters and associations and CO surveys of molecular clouds (Va´zquez et al. 2008);
- star forming complexes (Russeil 2003; Foster & Brunt 2014);
- masers associated with young, high-mass stars (Xu et al. 2006; Reid et al. 2014).

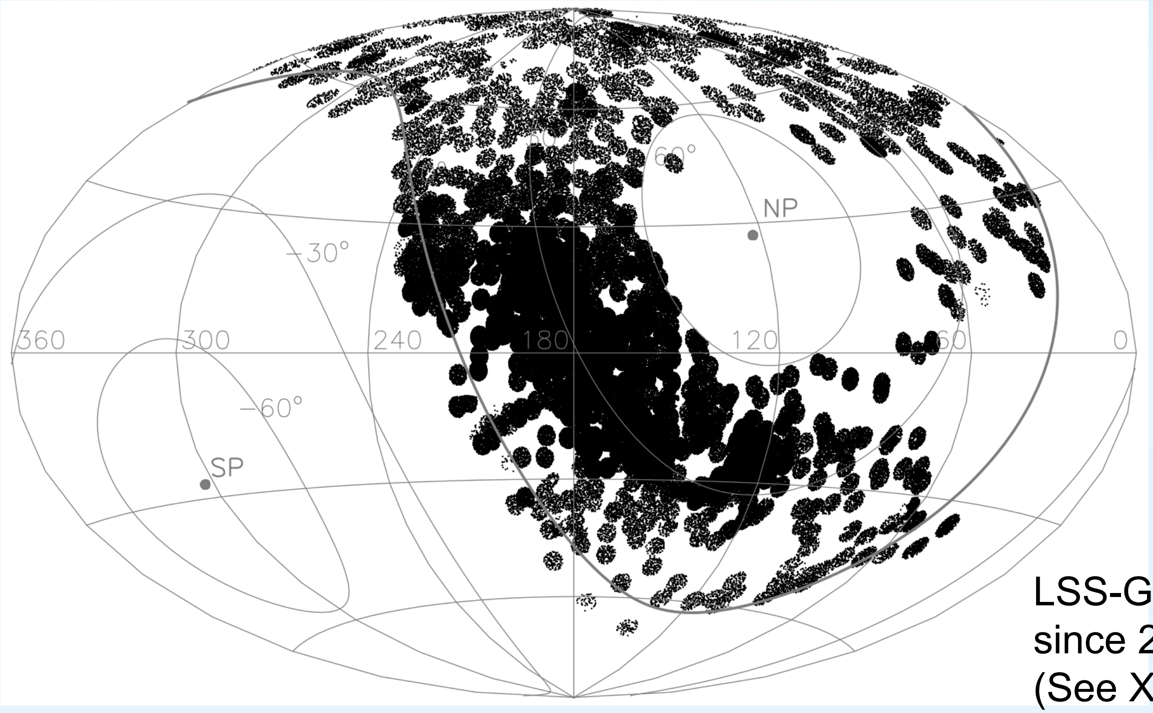
- Monguio et al. (2014)***: First detection of the field star overdensity in the Perseus arm;*** a *uvbyH*β Stromgren photometric survey; 16 deg^2 in the anticenter direction; OB stars
- Can we see a ring overdensity for the Perseus arm?



Monguio et al. (2014)

LSS-GAC value-added catalogue

- The LSS-GAC value-added catalogue provide us an unique opportunity for the above studies:
  - Continues sky coverage around the Galactic disk plane,
  - Large data sample,
  - Simple selection function,
  - Accurate stellar atmosphere parameters for different population selection
  - Accurate distance and extinction determinations

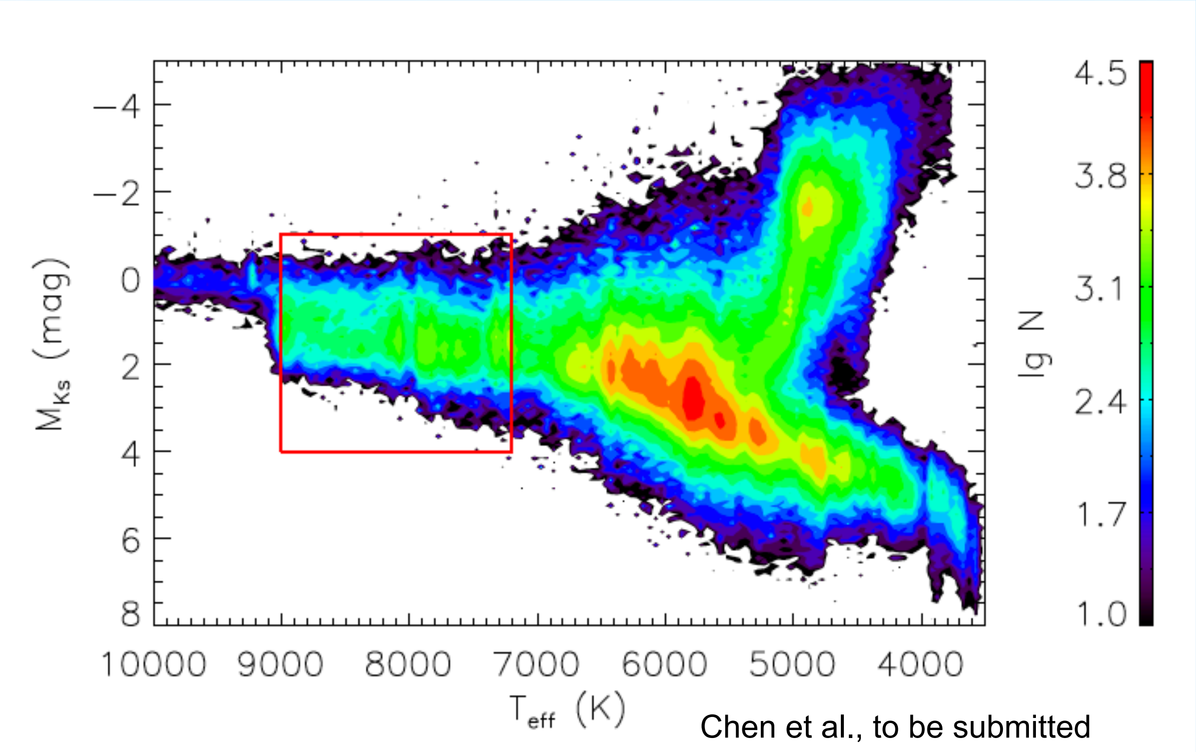


LSS-GAC data observed since 2015 November (See Xiang's report)

A-type stars

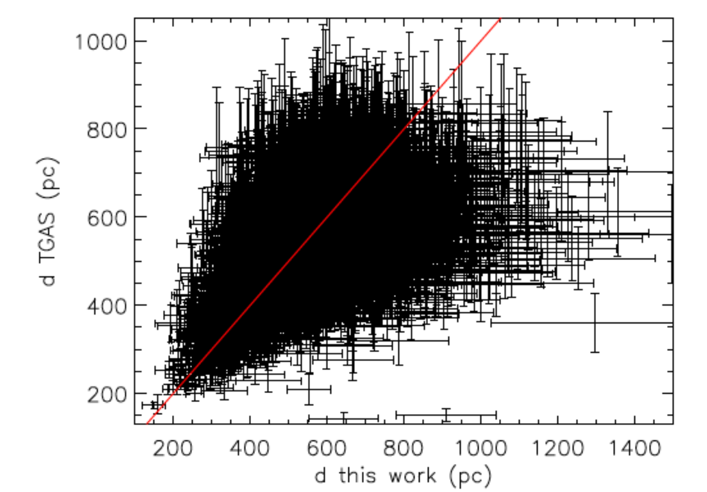
- A-type stars probe as good tracers for the Galactic thin disk analysis
  - Bright enough to reach large distances from the Sun
  - Homogeneous with respect to age (0.3 – 1 Gyr) to avoid the problems for samples which span a broad range of ages in previous works.

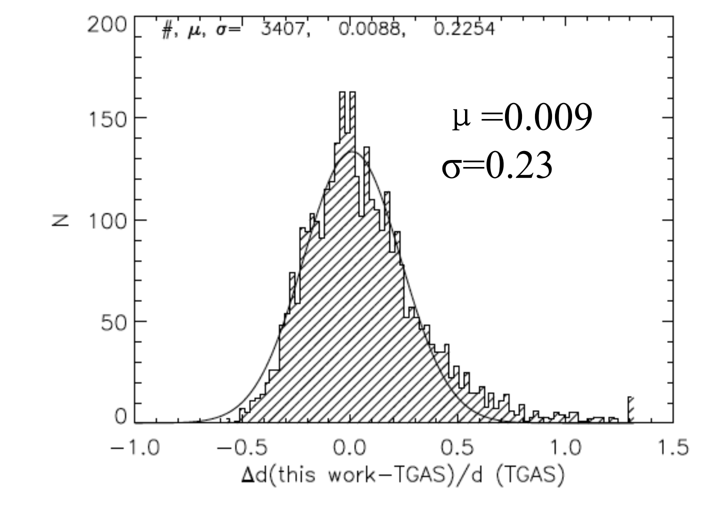
- We select A2V-A8V stars from LAMOST by 7200 < T_{eff} <9000 K

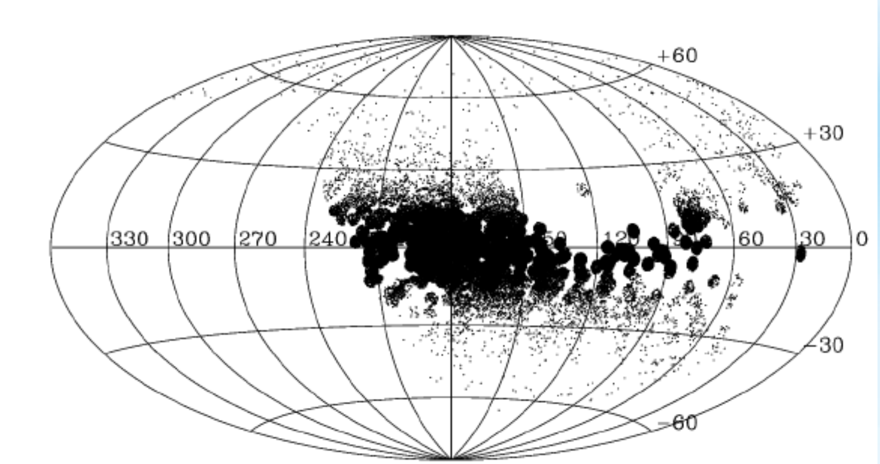


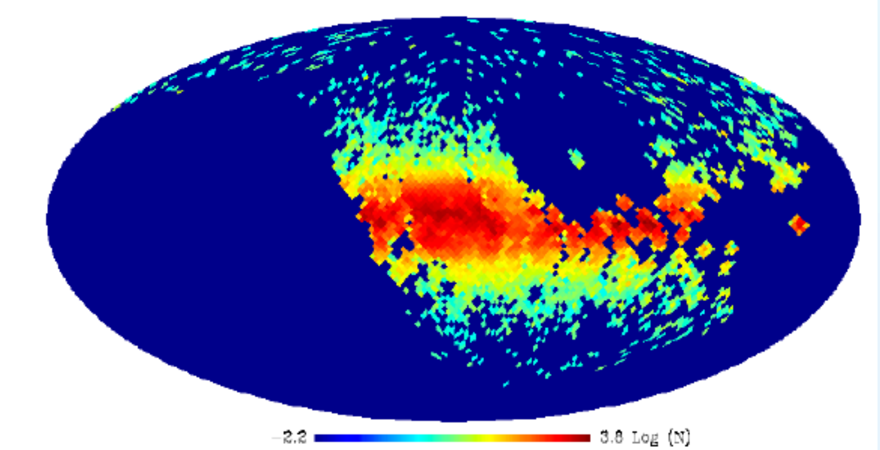
LSS-GAC A-type stars

- We selected over 0.12 million A-type stars from LSS-GAC (since 2015.10)
  - Extinction: star pair method (Yuan et al. 2013) and RJCE method
  - Distance: KPCA method using Hipparchus training set (Xiang et al. 2016)



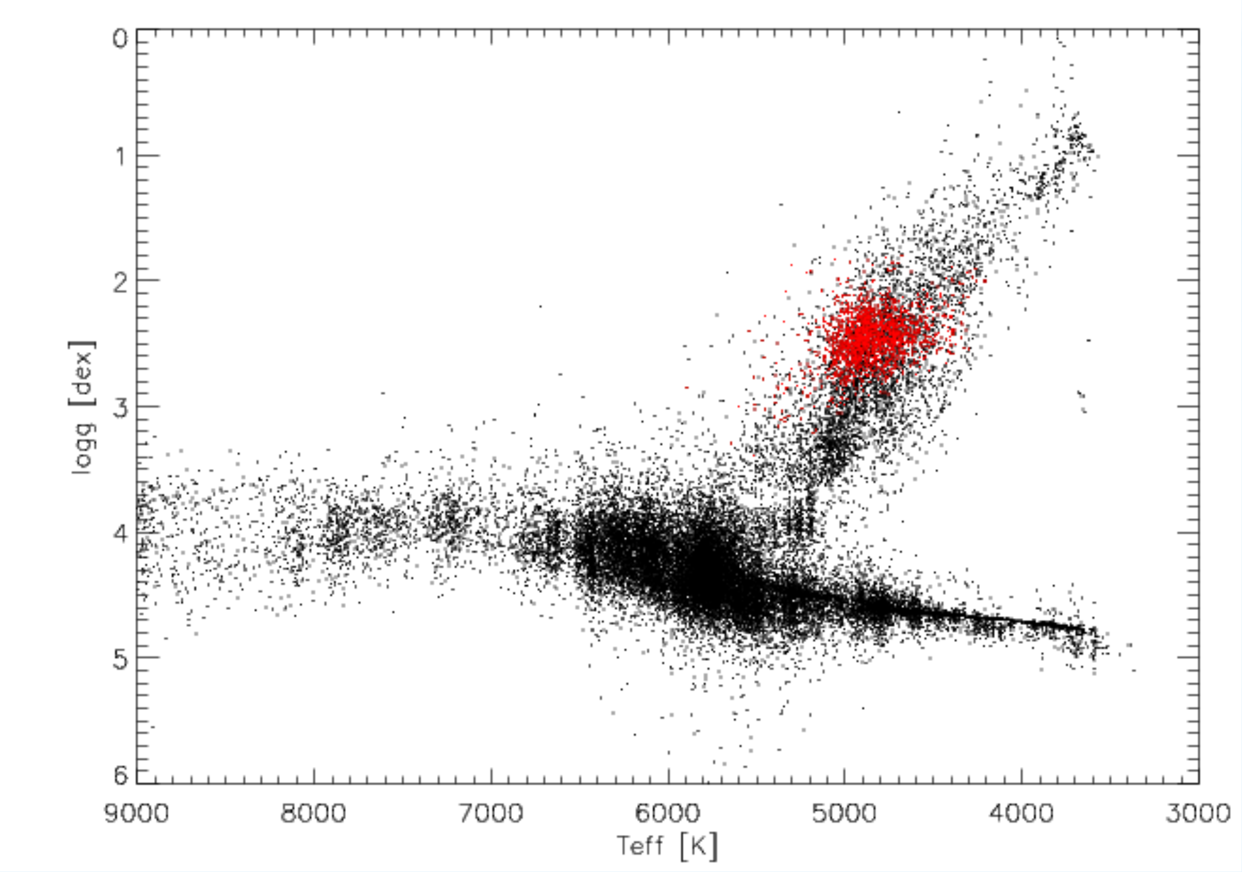






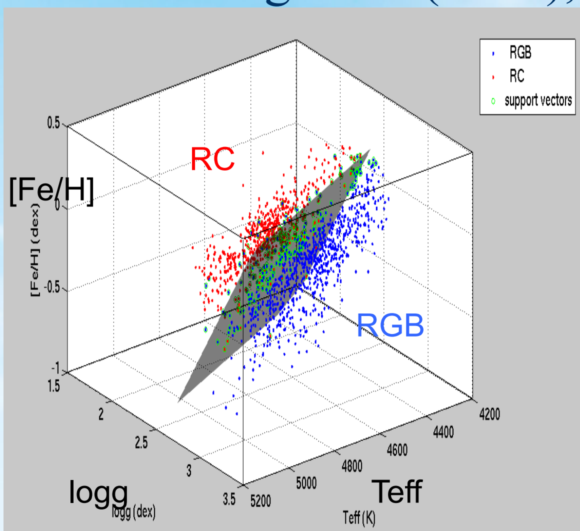
RC stars

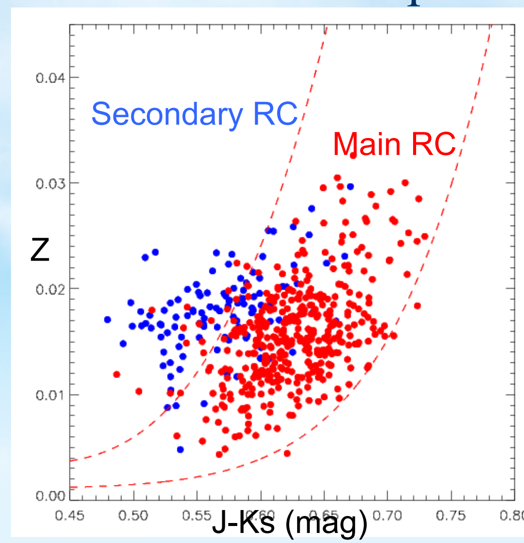
- RC stars probe as another good tracer for the Galactic disk analysis
  - Bright enough to reach large distances from the Sun (further than A stars)
  - Accurate distance estimation (5% - 10%)



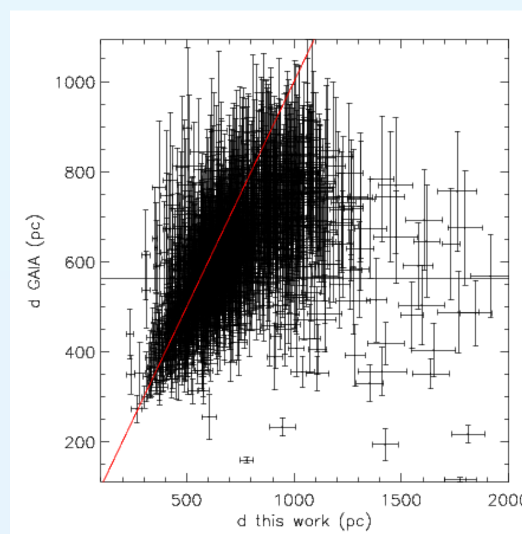
RC selection

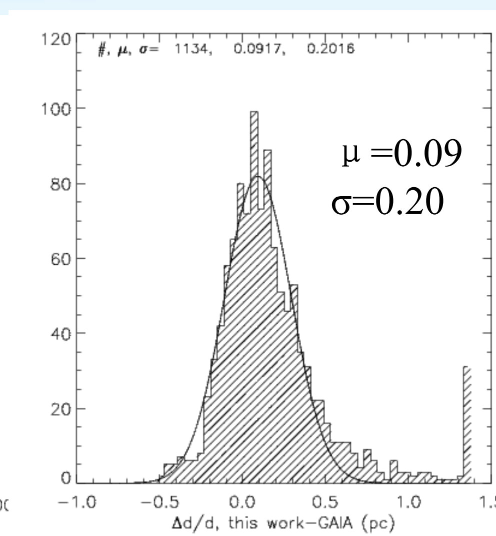
- Similar as in Huang et al. (2015), Trained from the sample of Stello et al. 2013





- Over 0.11 Million RC stars are selected from LSS-GAC DR2
  - Extinction: star pair method and RJCE
  - Distance: M_{Ks}= -1.61 mag





Method

- Selection function correction

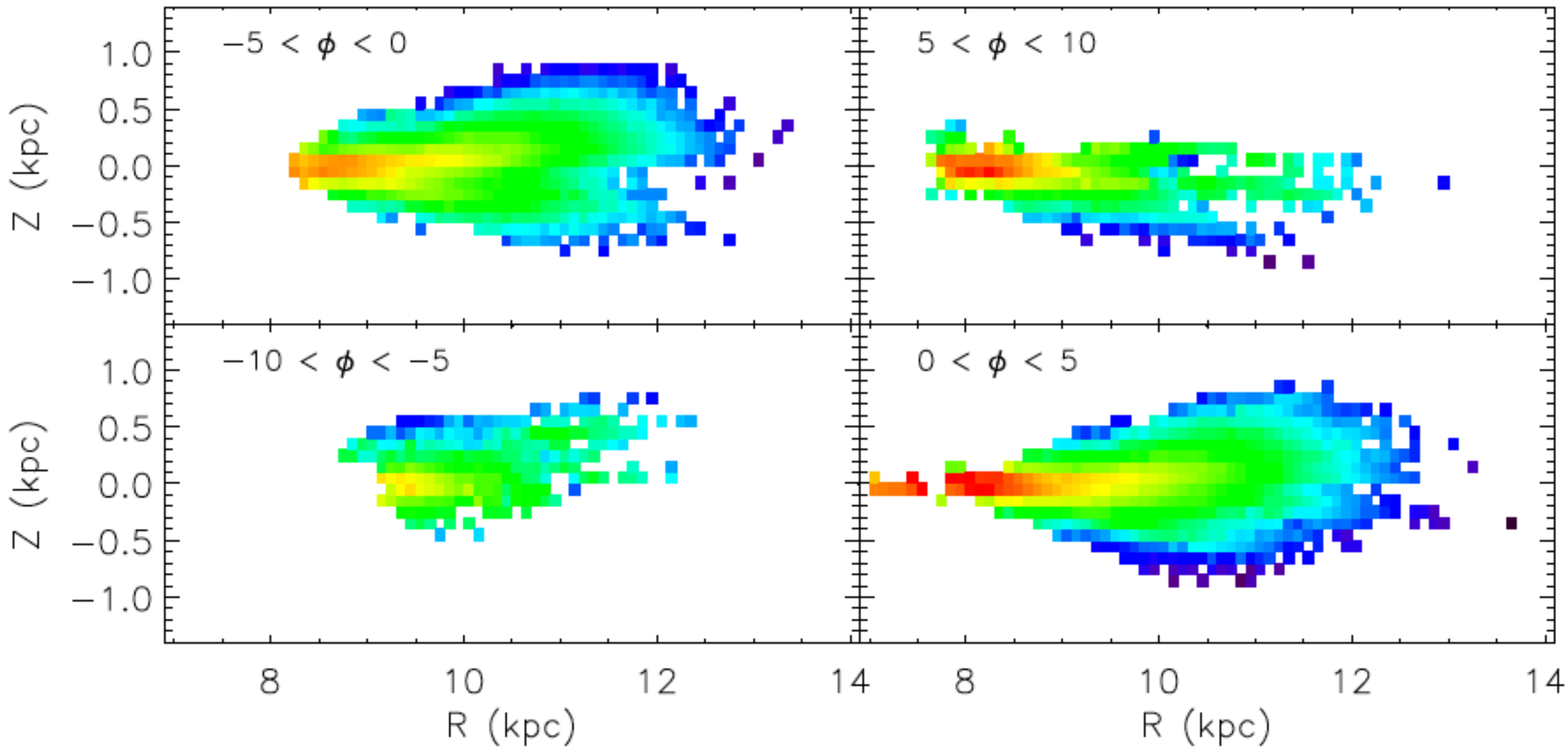
Table 2. Description of the weights of successfully observed stars in LSS-GAC DR2. Chen et al., to be submitted

Col.	Name	Description
1	spec_id	LAMOST unique spectral ID, in format of date-plateid-spectrographid-fibreid
2	plate	LAMOST plate ID, not necessarily unique
3	spectrograph	LAMOST spectrograph ID, ranging from 1 to 16
4	ra	Right ascension of J2000.0 (deg)
5	dec	Declination of J2000.0 (deg)
6	W_1(subfiled),X	Weight for target selection based on the XSTPS-GAC photometry
7	W_2(subfiled),X	Weight for successfully observed stars based on the XSTPS-GAC photometry
8	W(subfiled),X	Total election function calculated using the XSTPS-GAC photometry
9	W_1(subfiled),A	Weight for target selection based on the APASS photometry
10	W_2(subfiled),A	Weight for successfully observed stars based on the APASS photometry
11	W(subfiled),A	Total selection function calculated using the APASS photometry
12	W_1(subfiled),T	Weight for target selection based on the 2MASS photometry
13	W_2(subfiled),T	Weight for successfully observed stars based on the 2MASS photometry
14	W(subfiled),T	Total selection function calculated using the 2MASS photometry
15	W_1(pixel),X	Weight for target selection based on the XSTPS-GAC photometry
16	W_2(pixel),X	Weight for successfully observed stars based on the XSTPS-GAC photometry
17	W(pixel),X	Total selection function calculated using the XSTPS-GAC photometry
18	W_1(pixel),A	Weight for target selection based on the APASS photometry
19	W_2(pixel),A	Weight for successfully observed stars based on the APASS photometry
20	W(pixel),A	Total selection function calculated using the APASS photometry
21	W_1(pixel),T	Weight for target selection based on the 2MASS photometry
22	W_2(pixel),T	Weight for successfully observed stars based onthe 2MASS photometry
23	W(pixel),T	Total selection function calculated using the 2MASS photometry

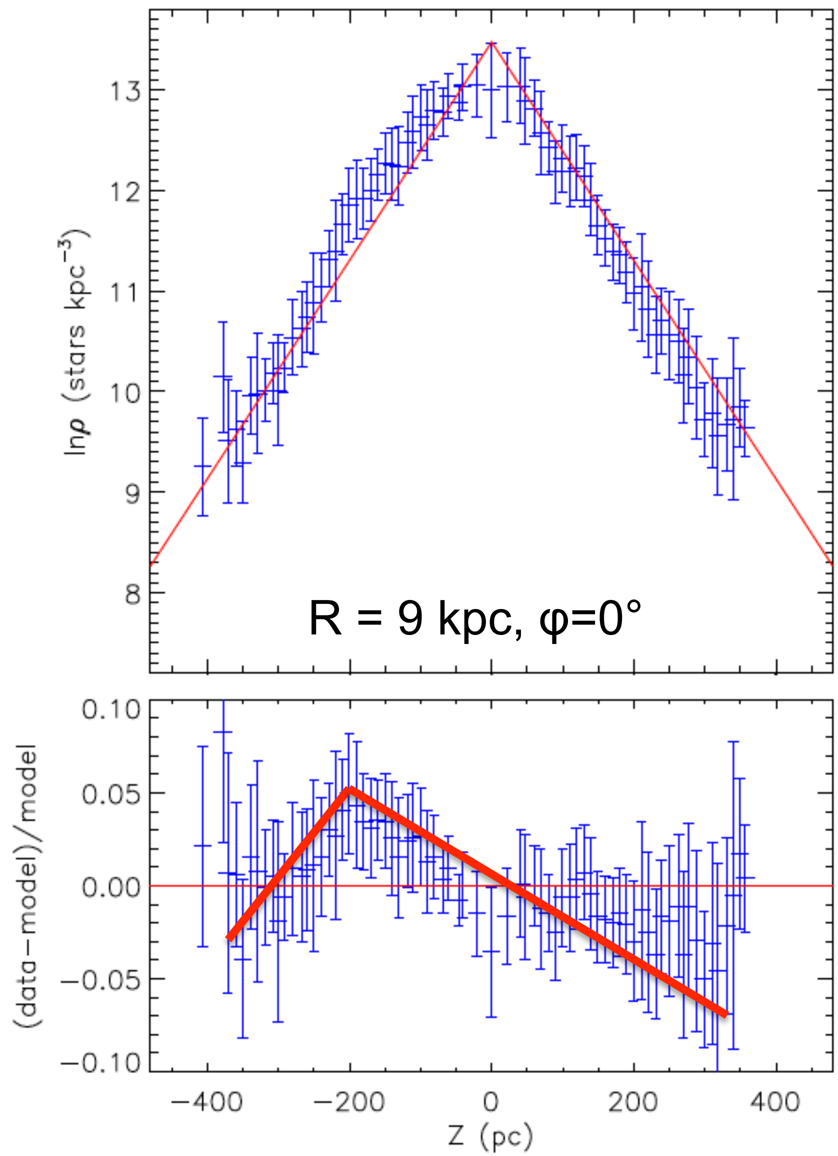
- Construction of the Density Maps

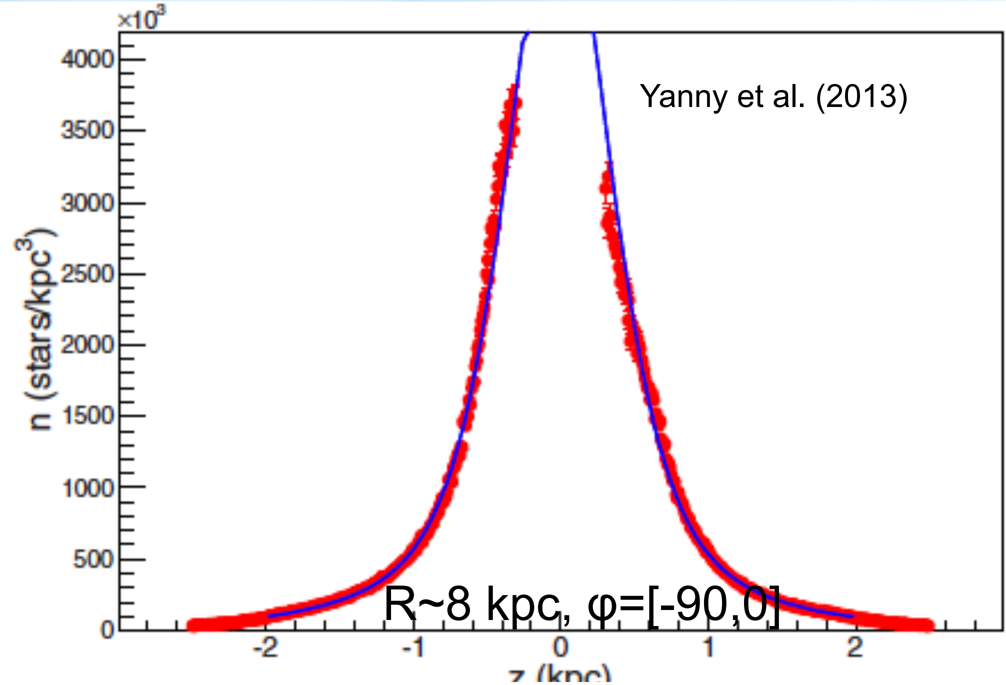
$$\rho(d_i) = \frac{\Sigma_{d_i}^{d_i+\delta d} W_i^{-1}}{C\Omega d_i^2 \delta d}$$

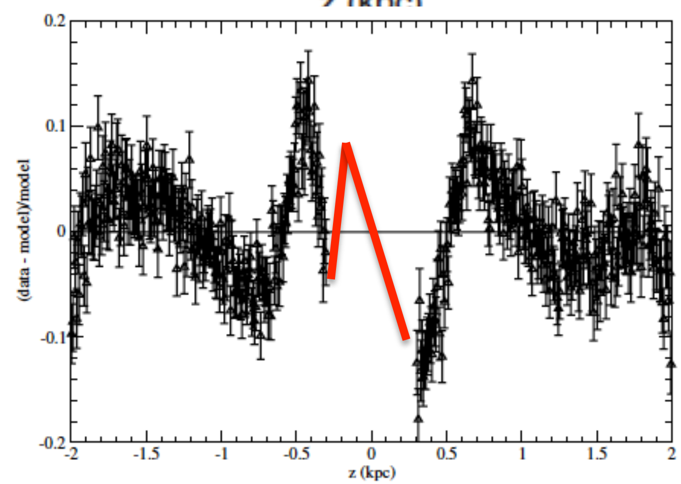
A stars: stellar number density maps



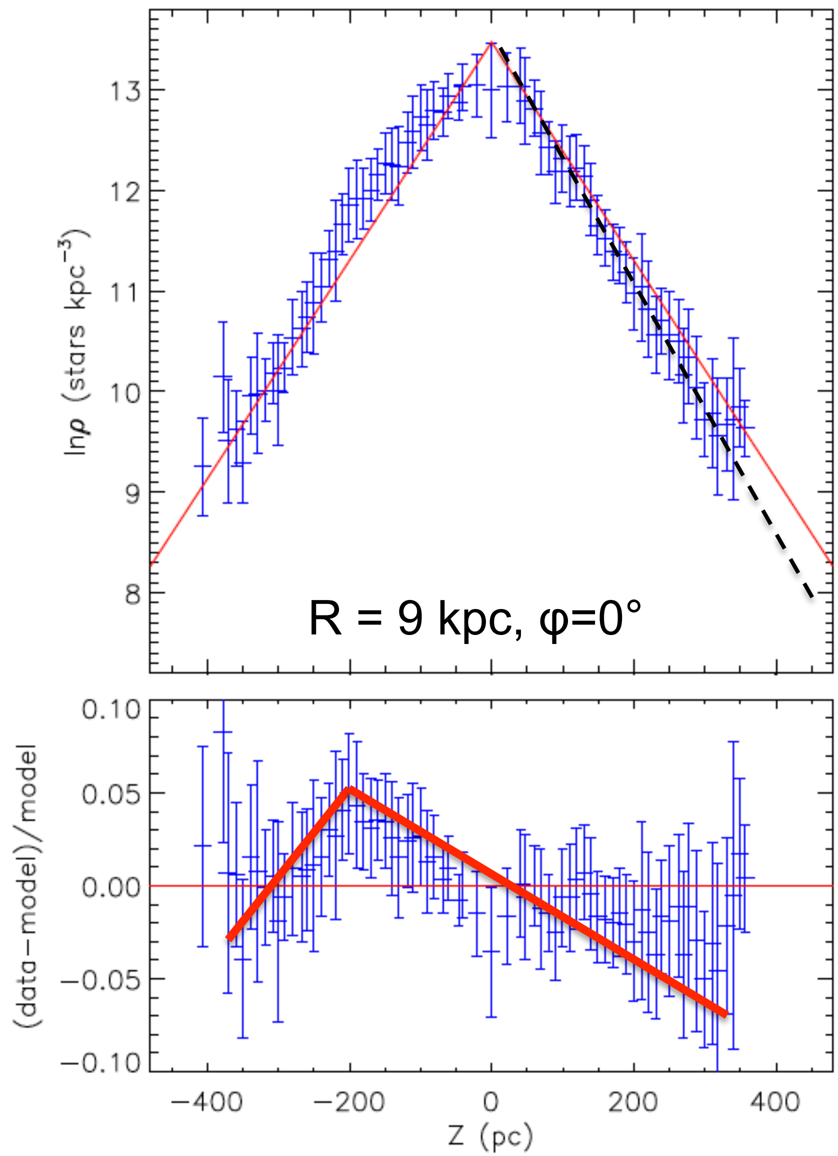
A stars: Z-dependent distribution

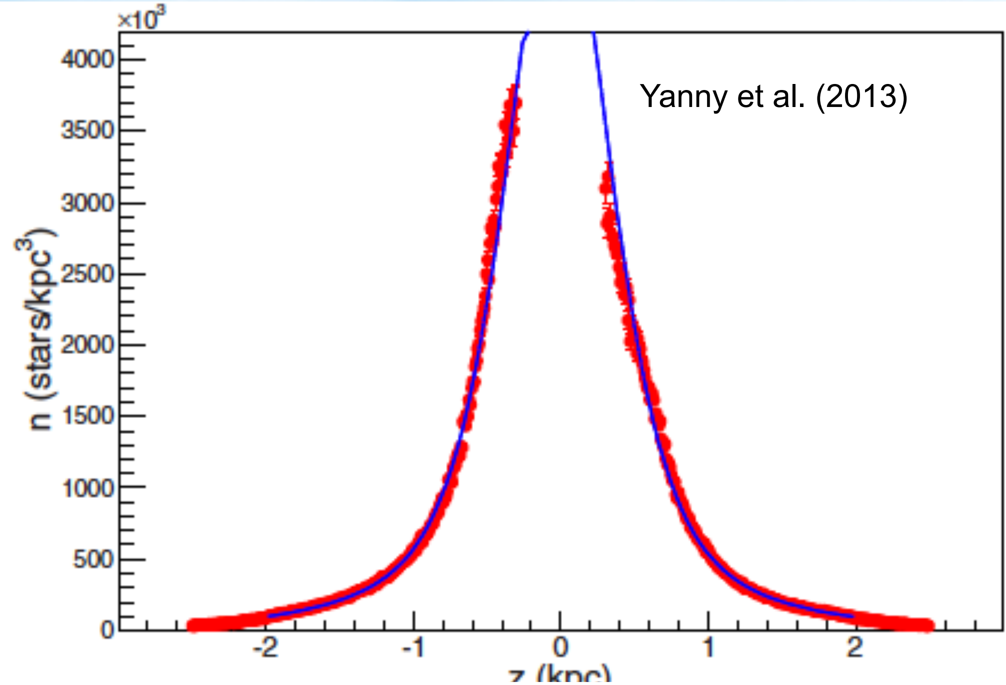


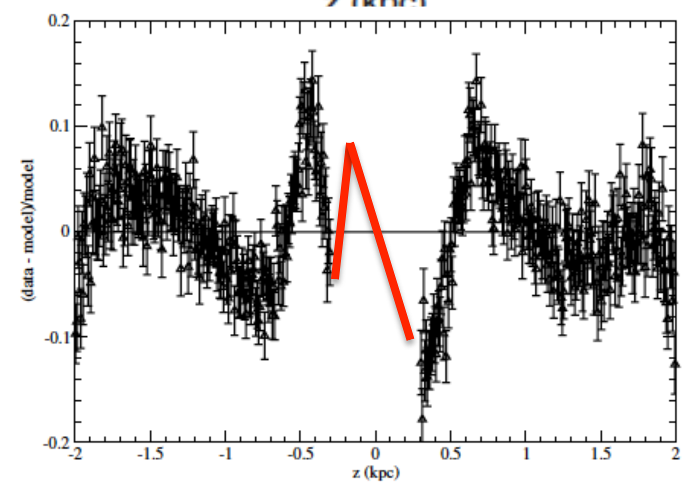




A stars: Z-dependent distribution







Disk flaring

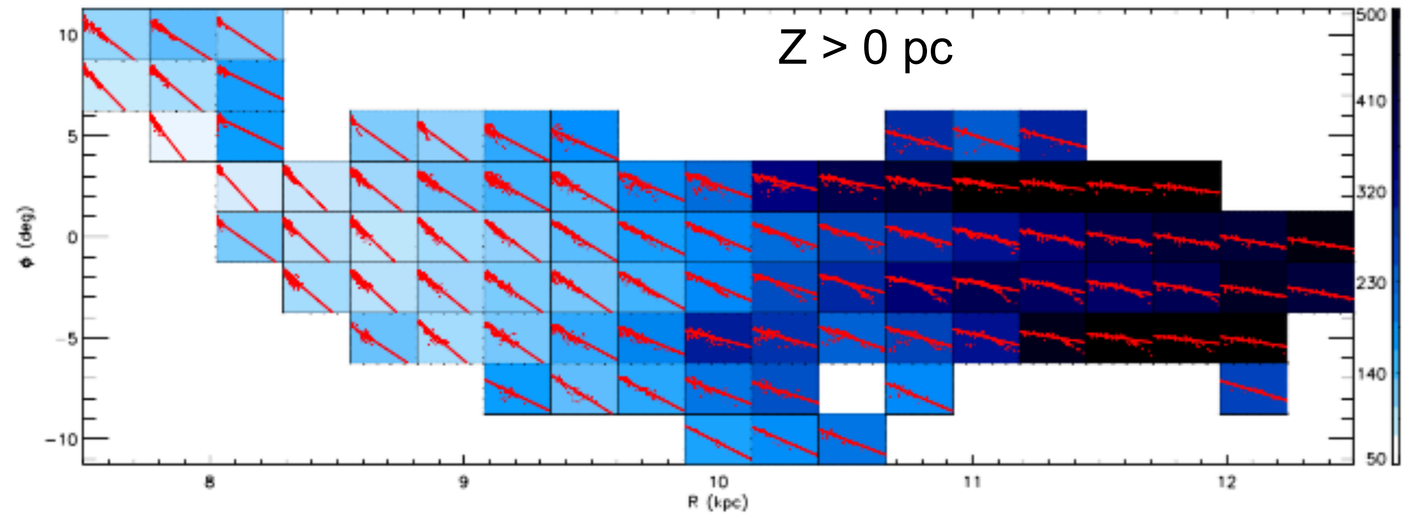


Figure 6. Disk flaring (color scale) derived with the our sample for stars in the North Galactic disk with $|Z| > 0$ kpc. Each sub-panel plots stellar number density $\ln\rho$ as a function of Z (points) along with a linear fit to the data (straight line). The horizontal axis of each sub-panel ranges ϕ from 10.5 to 10.5° and the vertical axis R from 7 to 13 kpc.

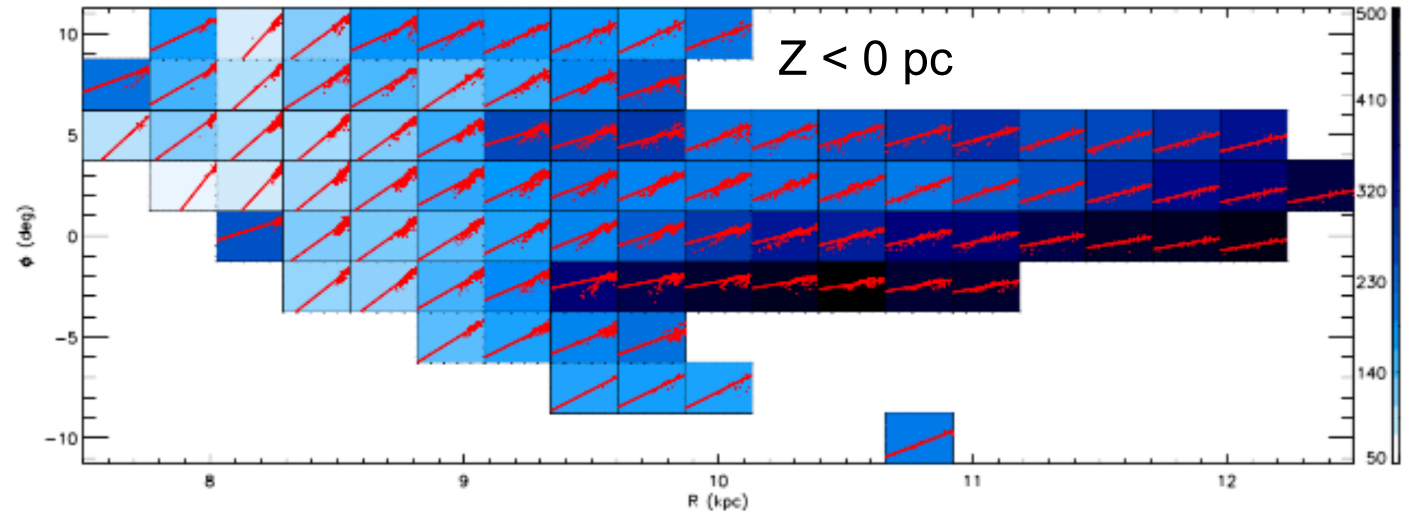
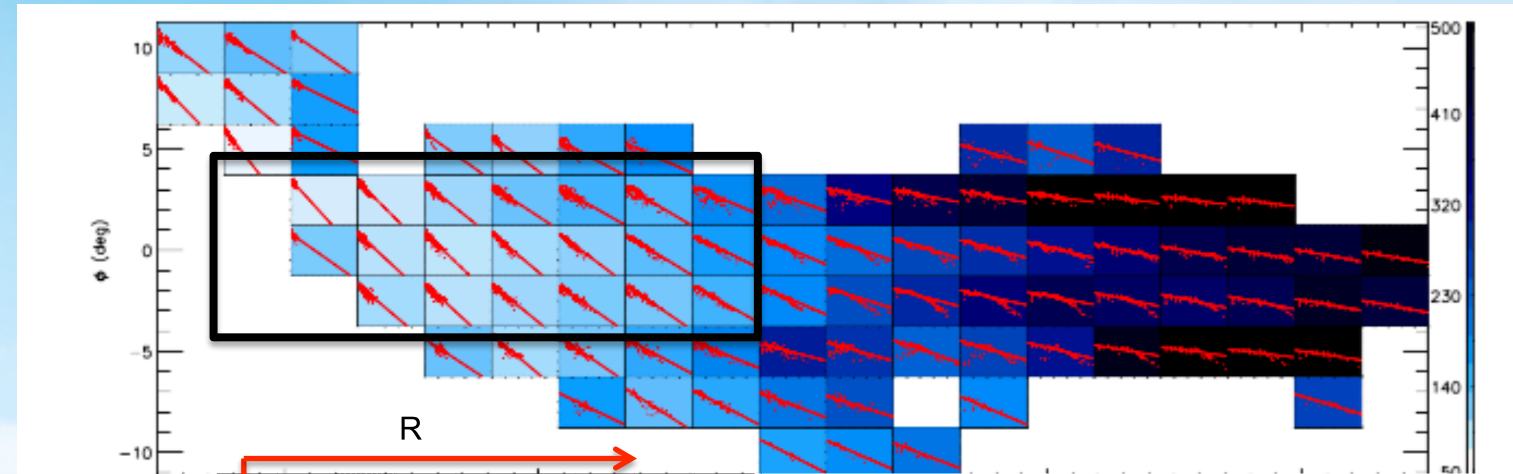
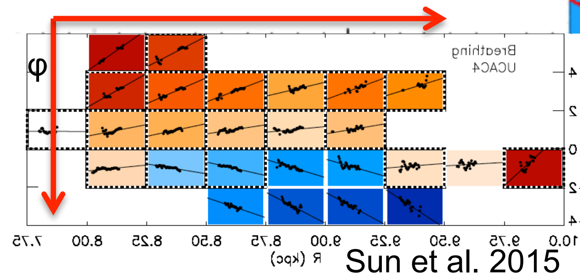


Figure 7. Same as Fig. 6 but for the South Galactic disk with $|Z| < 0$ kpc.

The breathing mode





As φ from 5 to -5°, h_z decreasing, i.e. from rarefaction to compression, i.e. the breathing mode. For R direction, hard to see the effect as the disk flaring

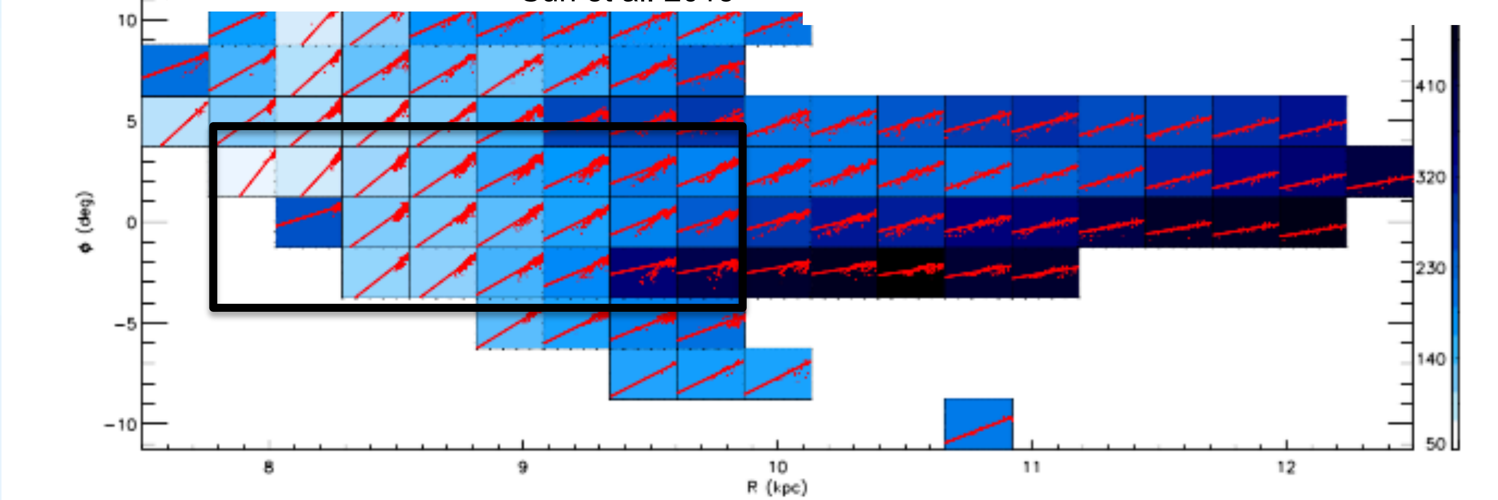


Figure 7. Same as Fig. 6 but for the South Galactic disk with $|Z| < 0$ kpc.

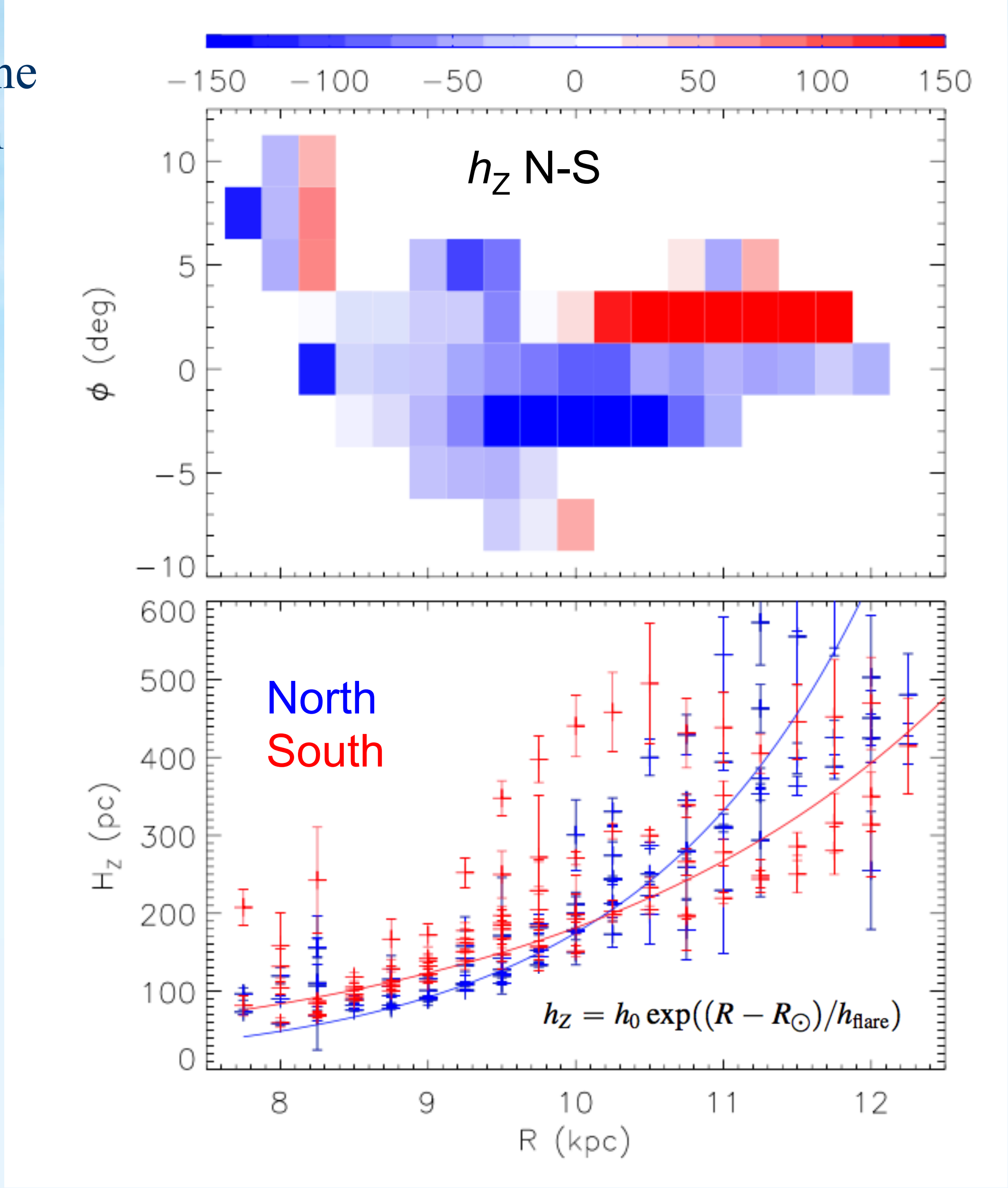
Disk flaring traced by A stars

- In the solar neighborhood, the scale height in the Northern Galactic disk is systematically smaller than the Southern disk

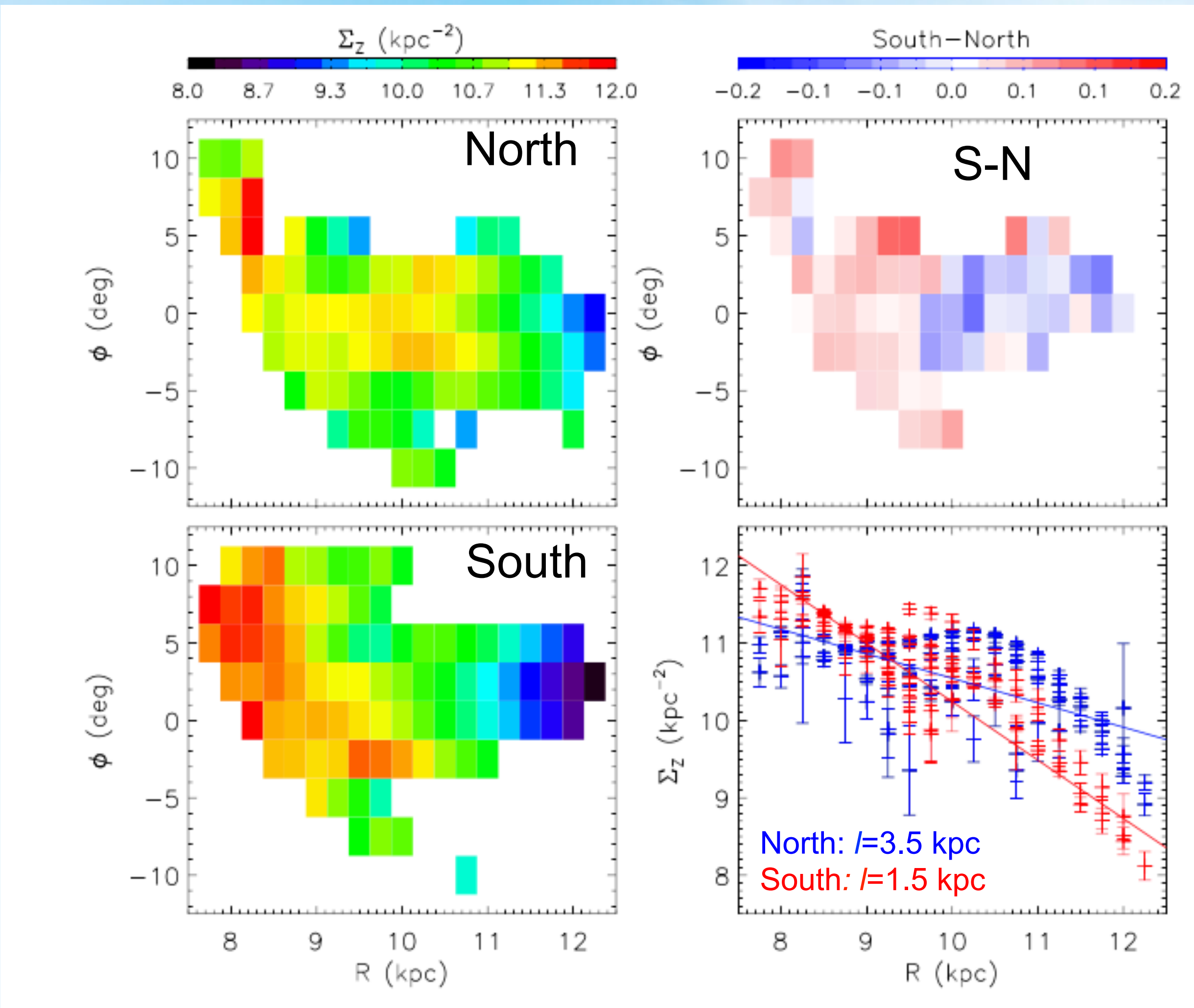
- The disk flaring is different between the Northern and South Galactic disk

North $h_Z = 49\exp((R - R_\odot)/1564)$

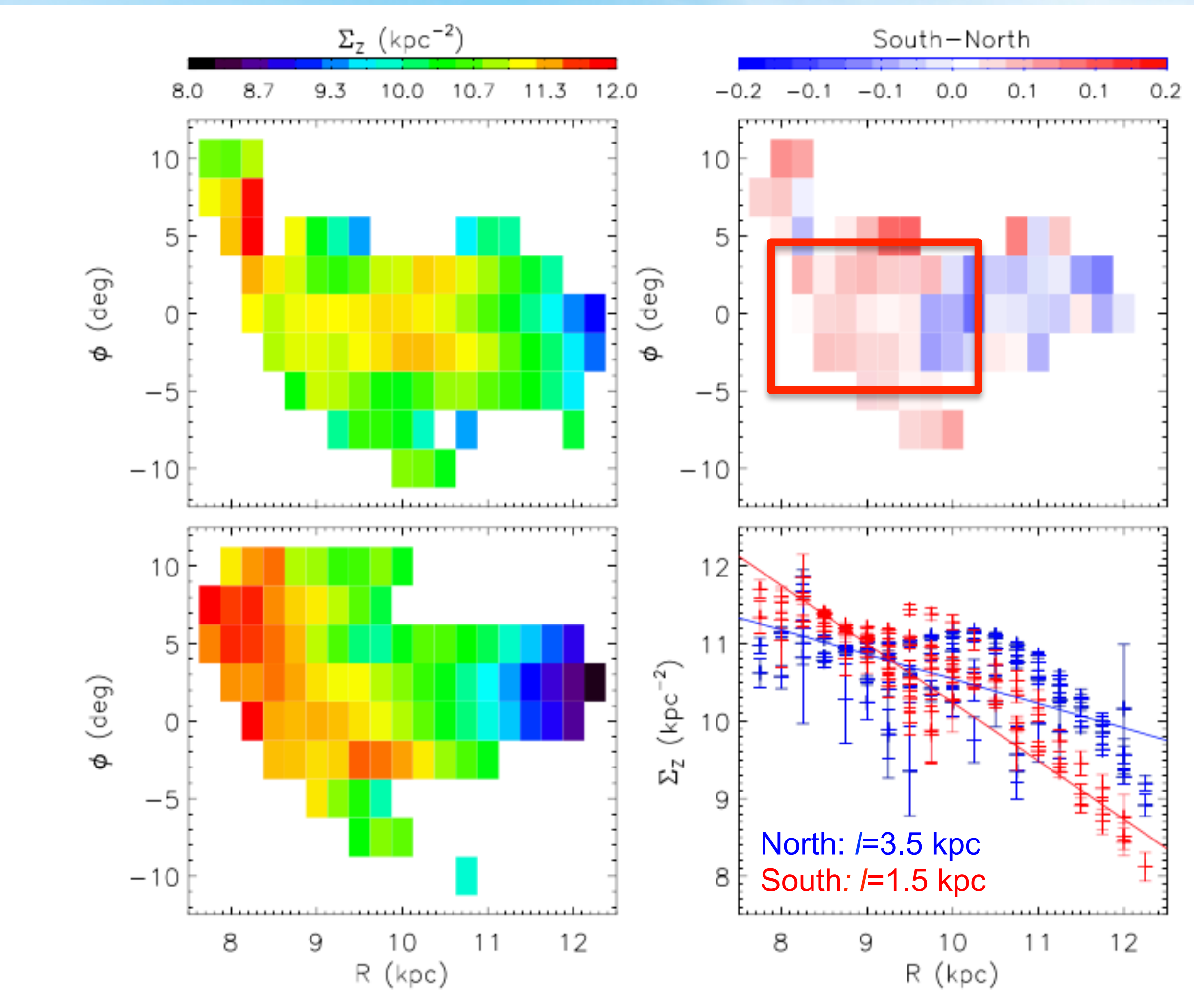
South $h_Z = 84\exp((R - R_\odot)/2590)$

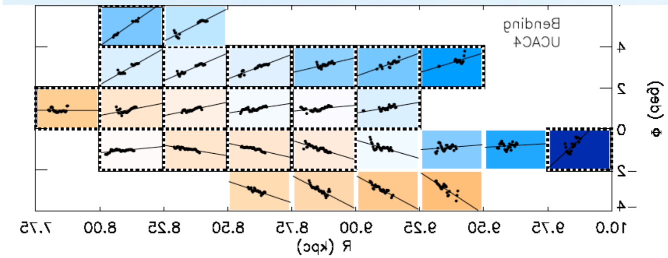


A stars: Radial distribution



Bending mode

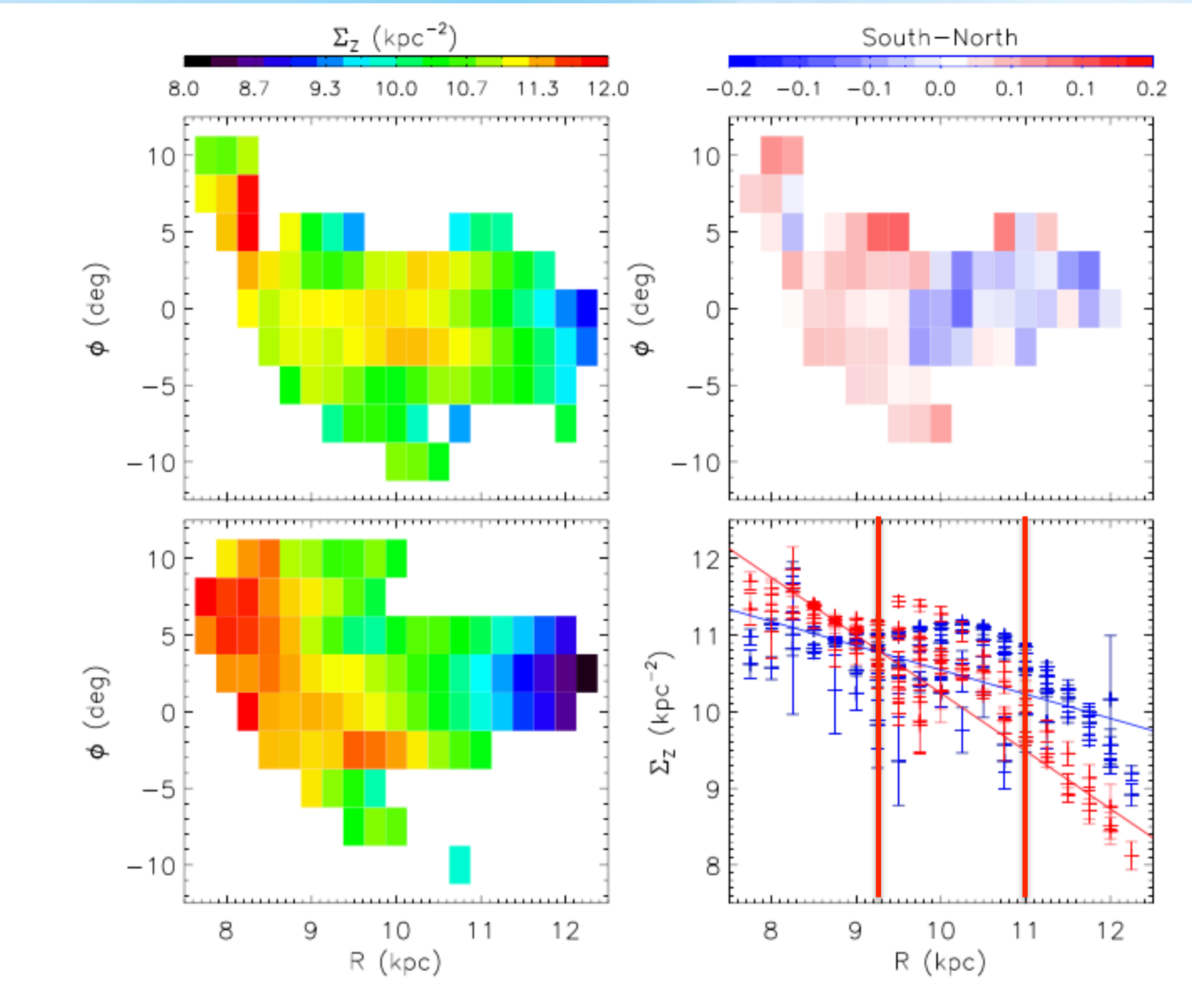


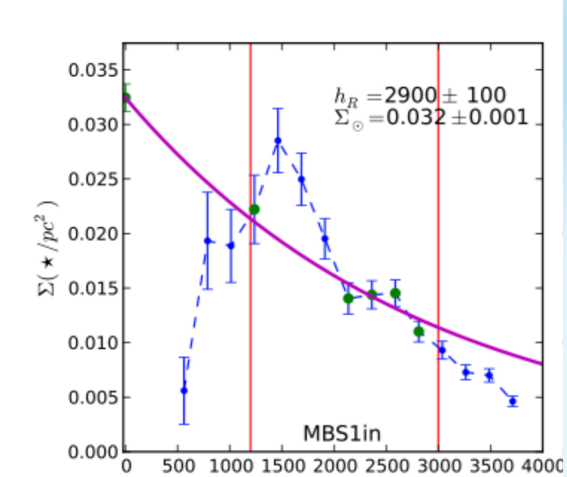


Sun et al. (2015)

- R<9.25: <V_Z> < 0; stars moving to South, S> N
- R>9.25: <V_Z> > 0; stars moving to North, N> S

The Perseus Arm overdensity





Monguio et al. (2014)

North: l=3.5 kpc

South: l=1.5 kpc

Mapping out the Perseus Arm

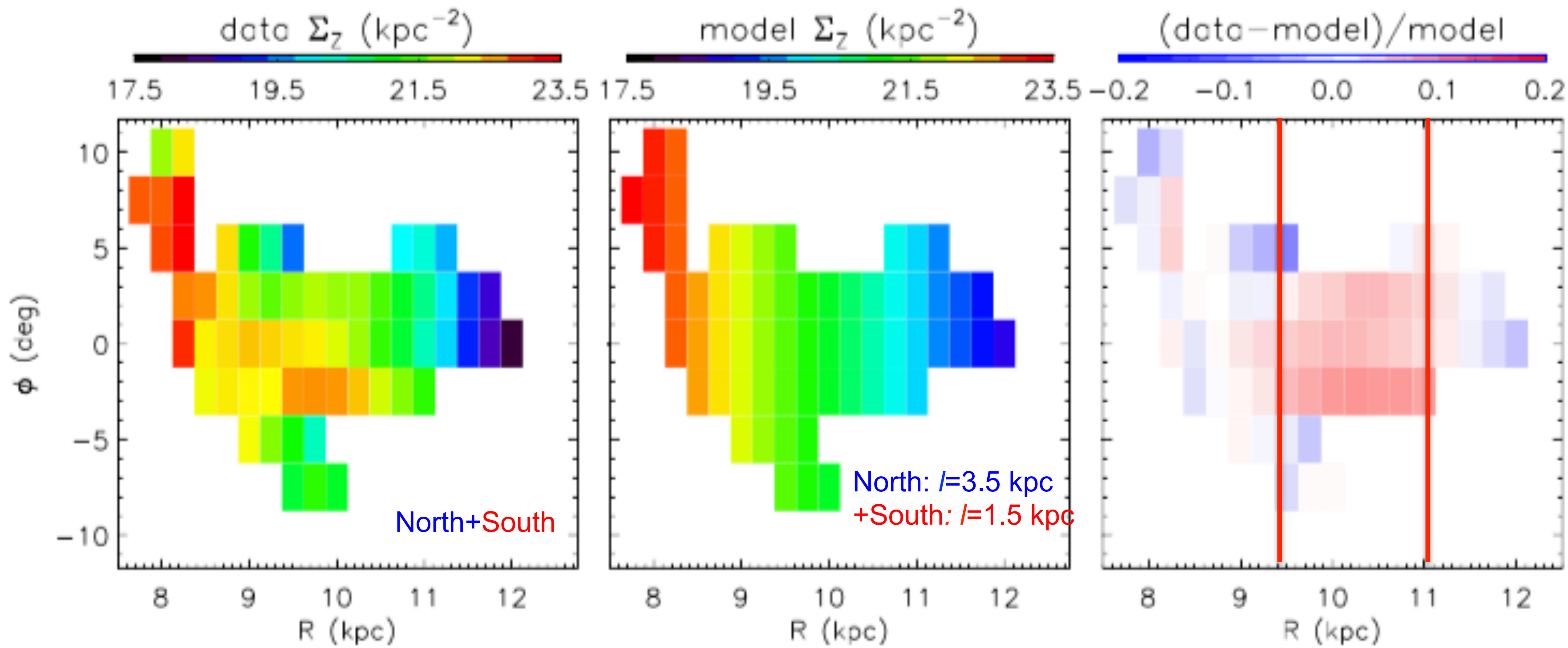
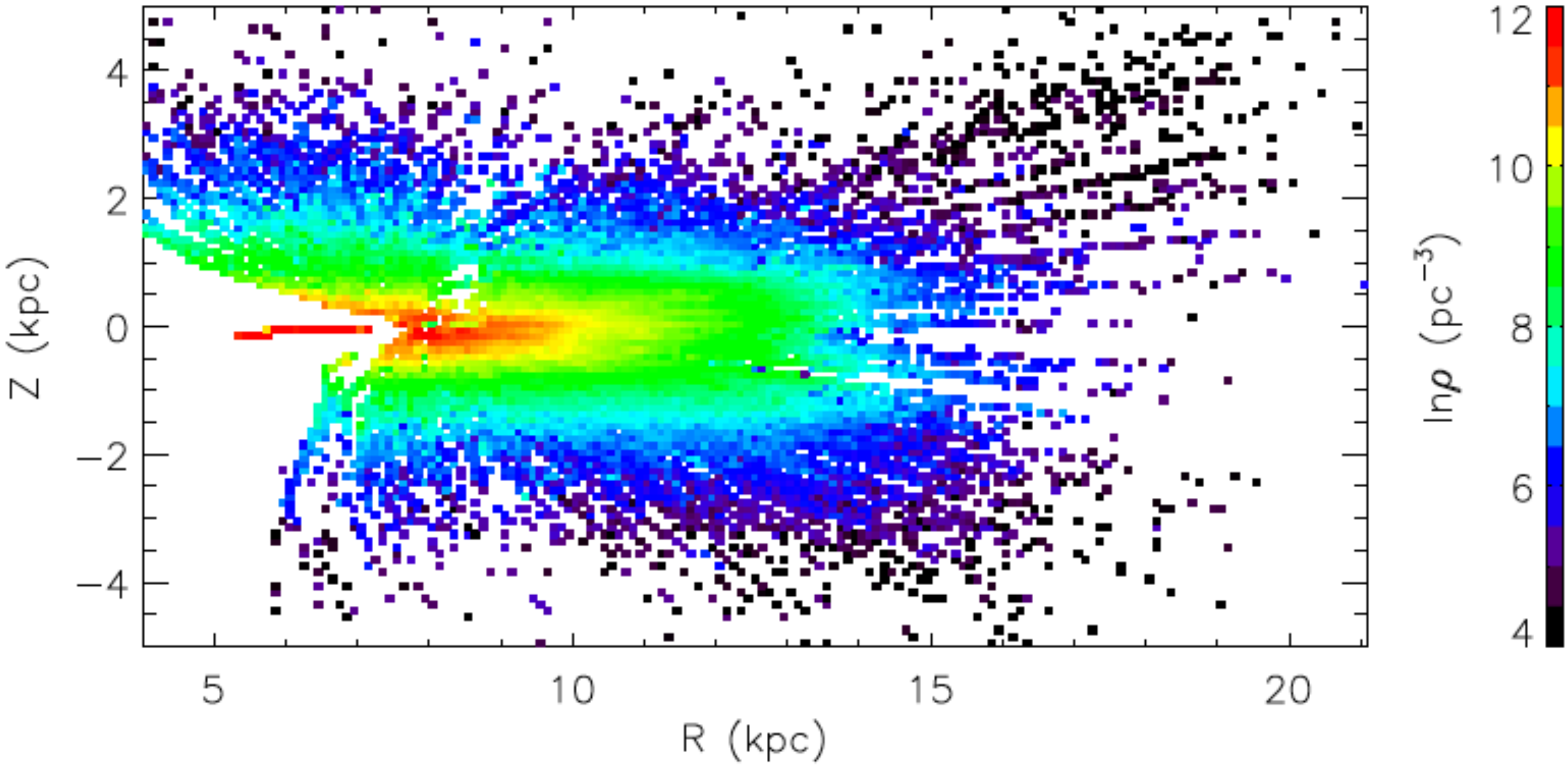
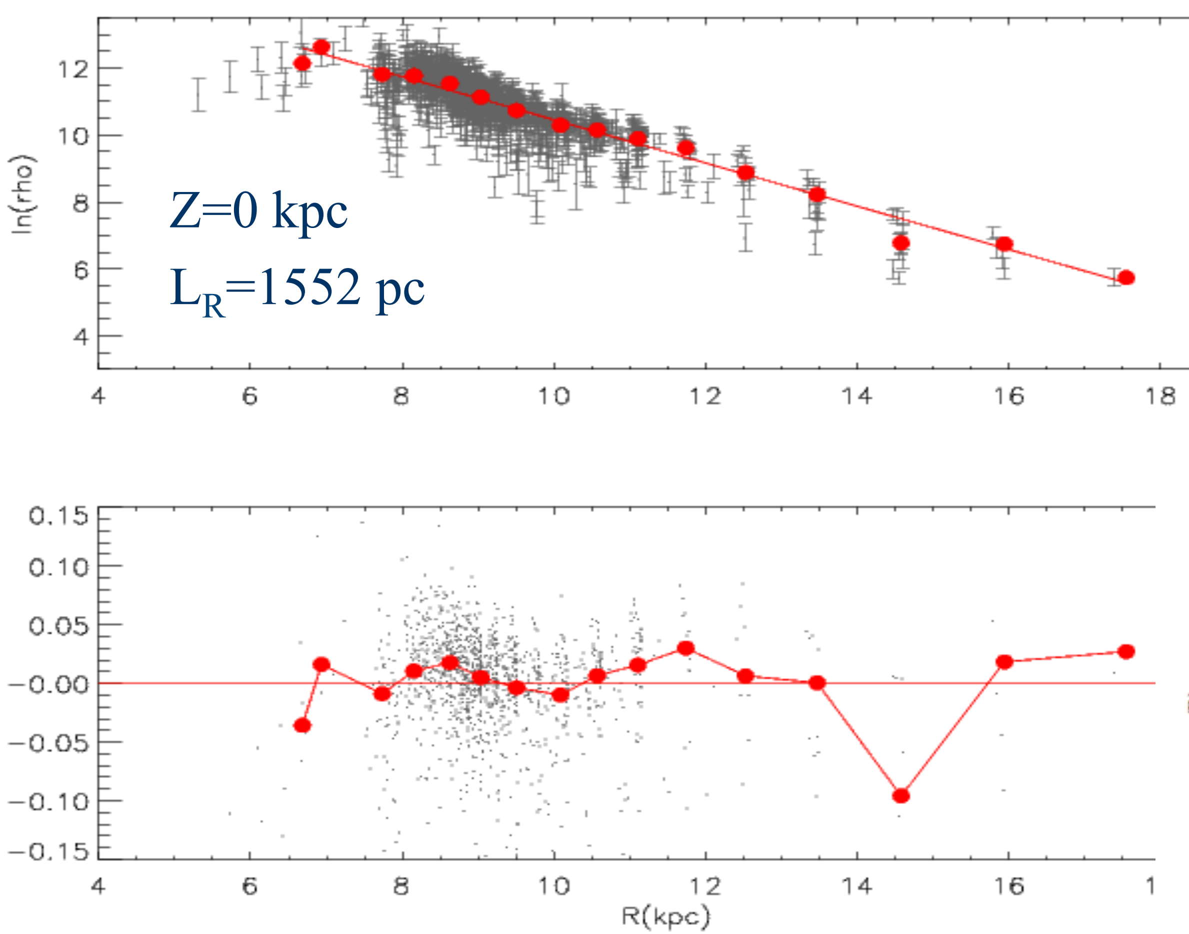


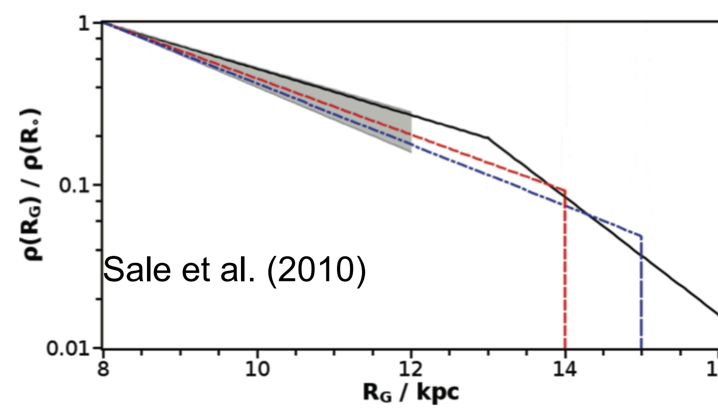
Figure 10. Radial variation of the stellar surface density for both the North and South samples in the current work. The left panel shows the data, the middle panel shows the best-fit model, and the right panel shows (data-model) residuals, normalized to the model. The residuals are shown on a linear stretch, from −20% to +20%. Note the excellent agreement of the data and the model and the overdensities in the region $9 < R < 11$ kpc possibly for the Perseus Arm.

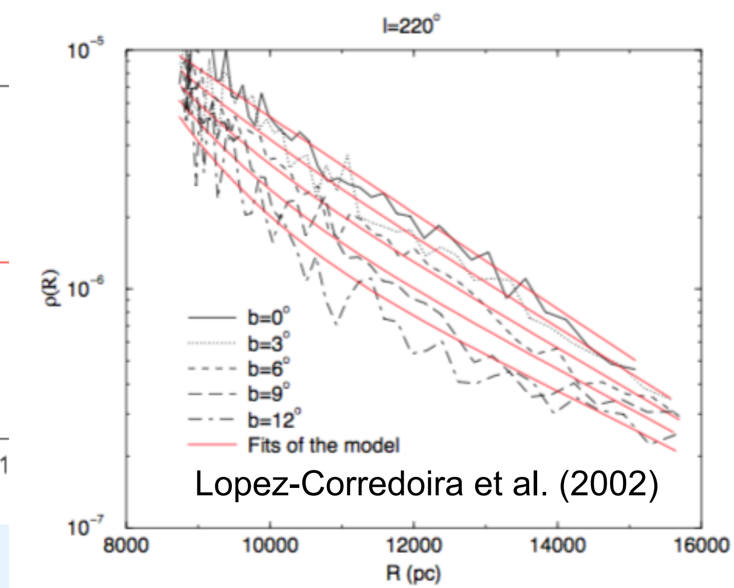
RC stars: number density maps



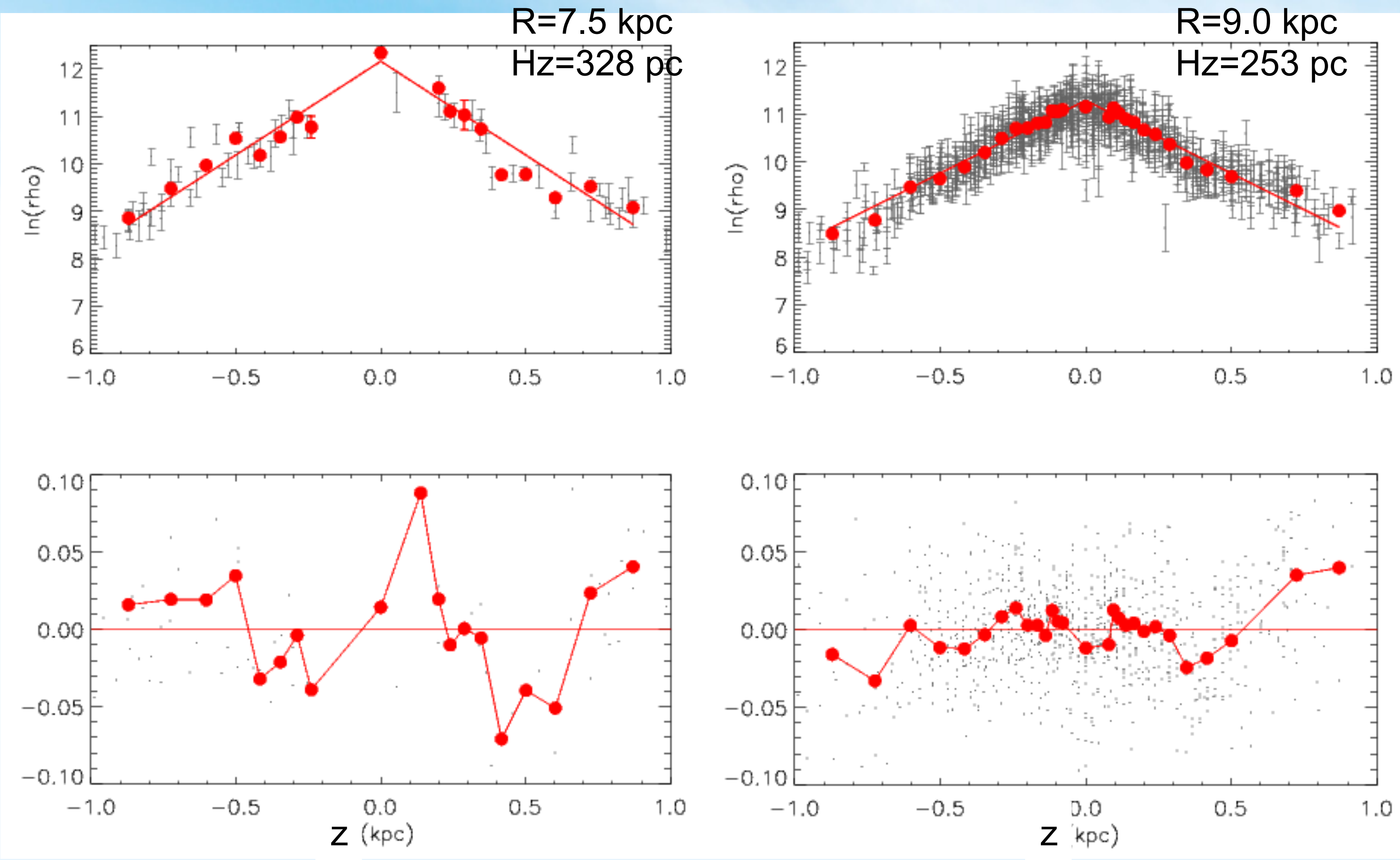
RC stars: Truncation or wave?



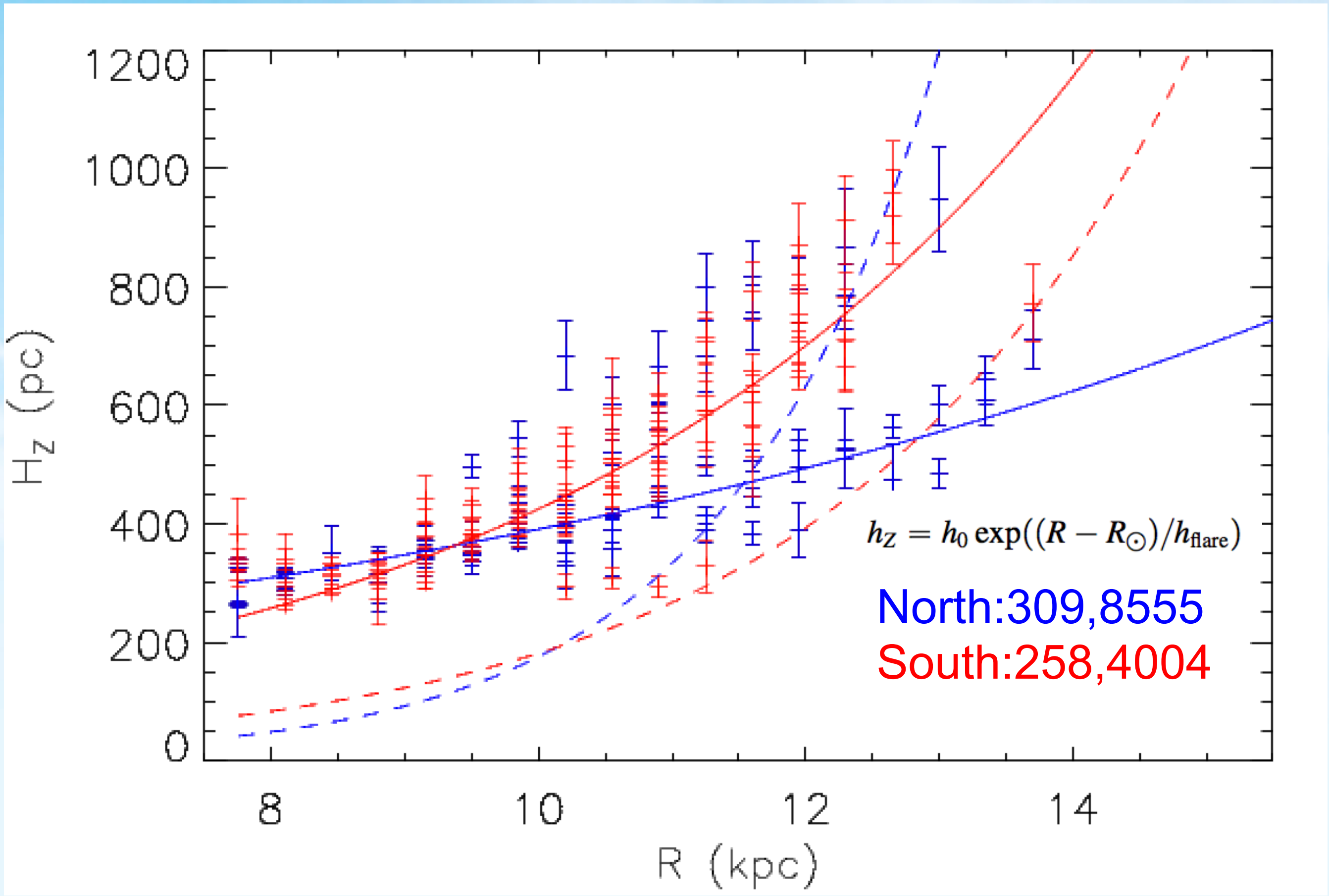




RC stars: N-S asymmetry



Disk flaring traced by RC stars



- The disk flaring is different between the Northern and South Galactic disk.
- Disk flaring traced by RC stars is much weaker than that traced by the A stars.

Summary

- We report a detailed investigation of the (sub)structure of the Galactic stellar disk, based on two samples selected from the LSS-GAC DR3:
  - A sample containing ~ 0.12 million A stars out to R ~ 14 kpc
  - A sample containing ~ 0.11 million red clump stars out to R ~ 18 kpc

- Based on the A stars, we find:
  - Strong stellar flaring of the Galactic young disk: much stronger than that found by other tracers; Northern disk different from Southern disk
  - Fine substructures: "breathing mode" and "bending mode" perturbations
  - The overdensity of the Perseus Arm

- Based on the RC stars, we find:
  - No truncation until R ~ 18kpc and "waves" like residuals
  - Galactic disk stellar flaring weaker than that traced by the A stars: the stellar flaring correlation with stellar ages