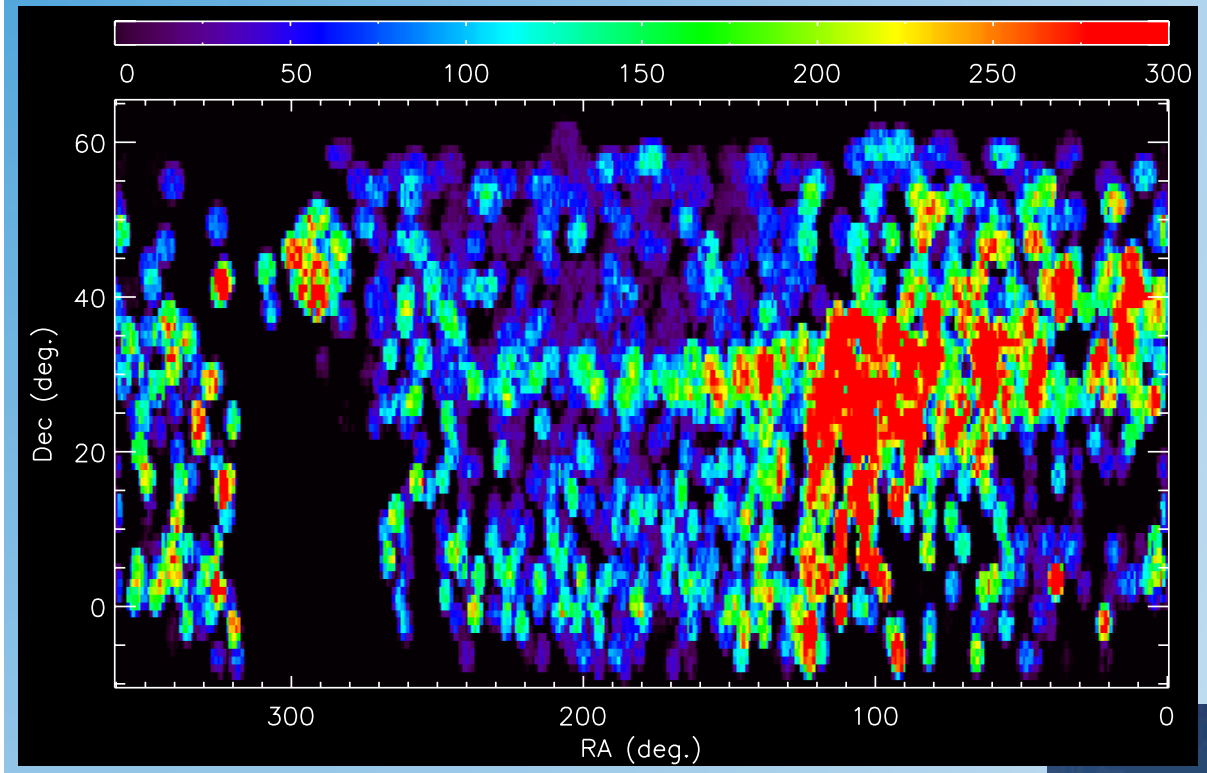


The LAMOST view of Galactic halo substructure

Jeff Carlin

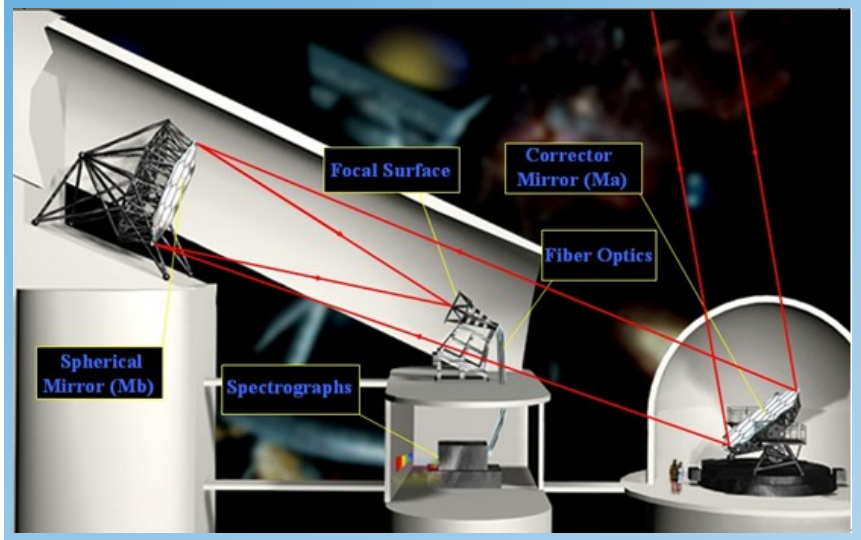
Earlham College & Rensselaer Polytechnic Institute

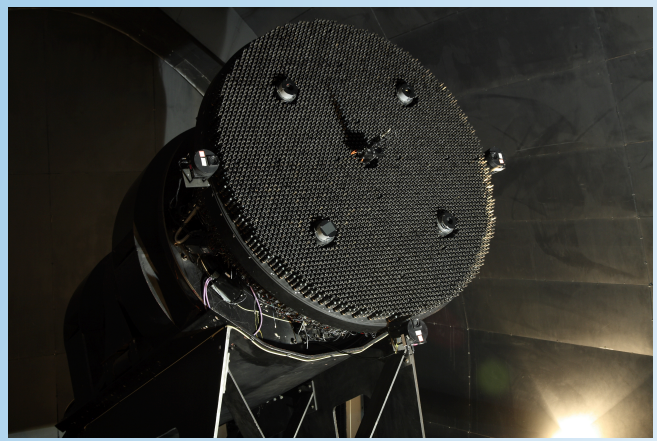
ESO Chile, Santiago, April 13, 2015

Outline

- LAMOST spectroscopic survey
  - tools to exploit LAMOST data
- Satellites and streams with LAMOST
  - Sagittarius stream
  - level of substructure in the halo
- Satellites' effects on galaxy structure
  - Wiggles in the Milky Way disk

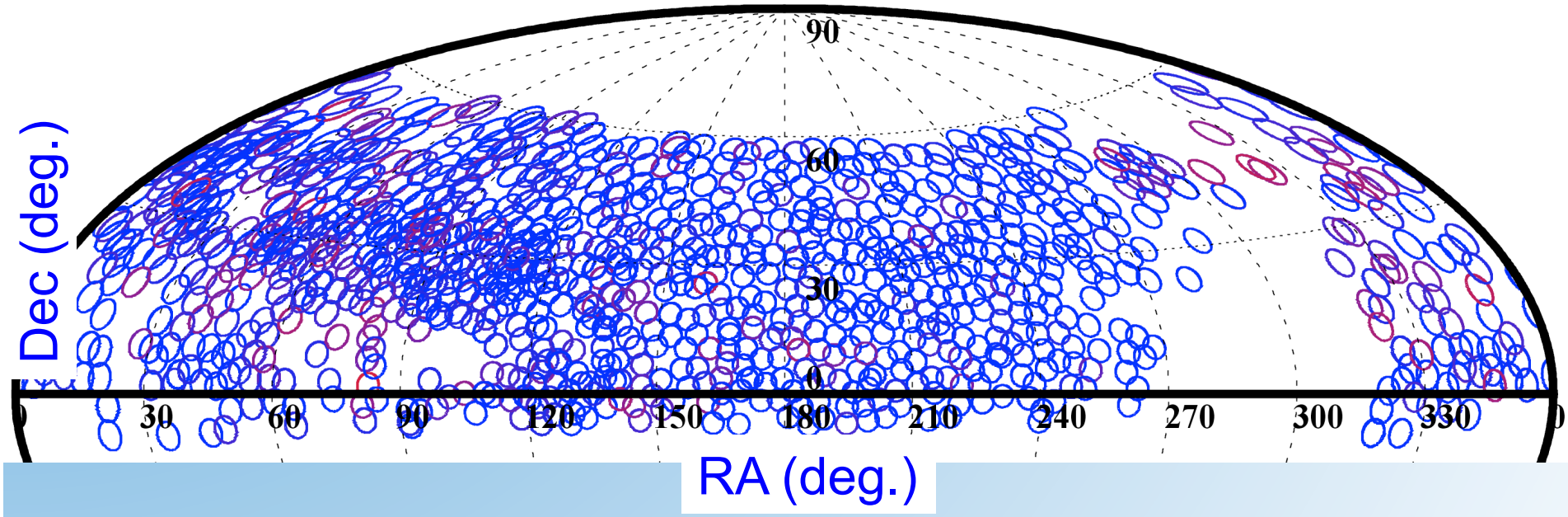
LAMOST survey





- Located in N. China (40° N lat.)
- 4 meter effective aperture
- 4000 fibers in focal plane of 5° (1.75m) diameter
- 16 bench spectrographs
- Sky coverage: Dec > -10°
- Wavelength range: 3700-9000 Å
- Resolution (λ/Δλ): 1800
- Public Data Release 1: http://dr1.lamost.org/

LAMOST survey footprint



Distribution of 2192 LAMOST plates observed Oct. 2011 – Apr. 7, 2015

→ ~4.5 million spectra available

(~2.0 million unique stars with stellar parameters, most with r < 17 mag)

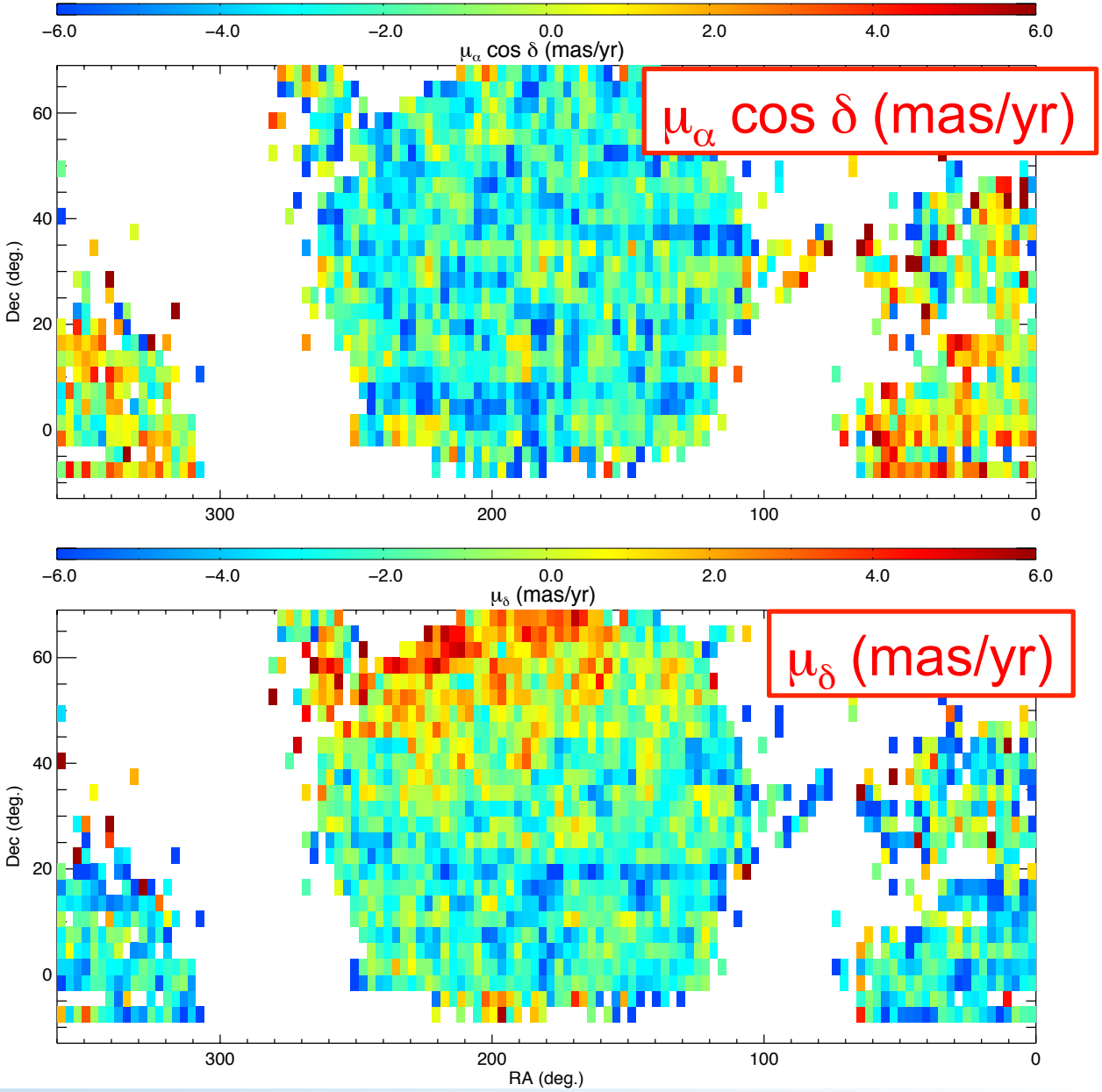
Developing the tools for studying Galactic structure with LAMOST

- proper motion corrections
- distances (derived from stellar parameters)
- K-giant classification (SVM-based; for low S/N spectra)
- M-giant classification (template matching)

Correcting PPMXL proper motion zero points

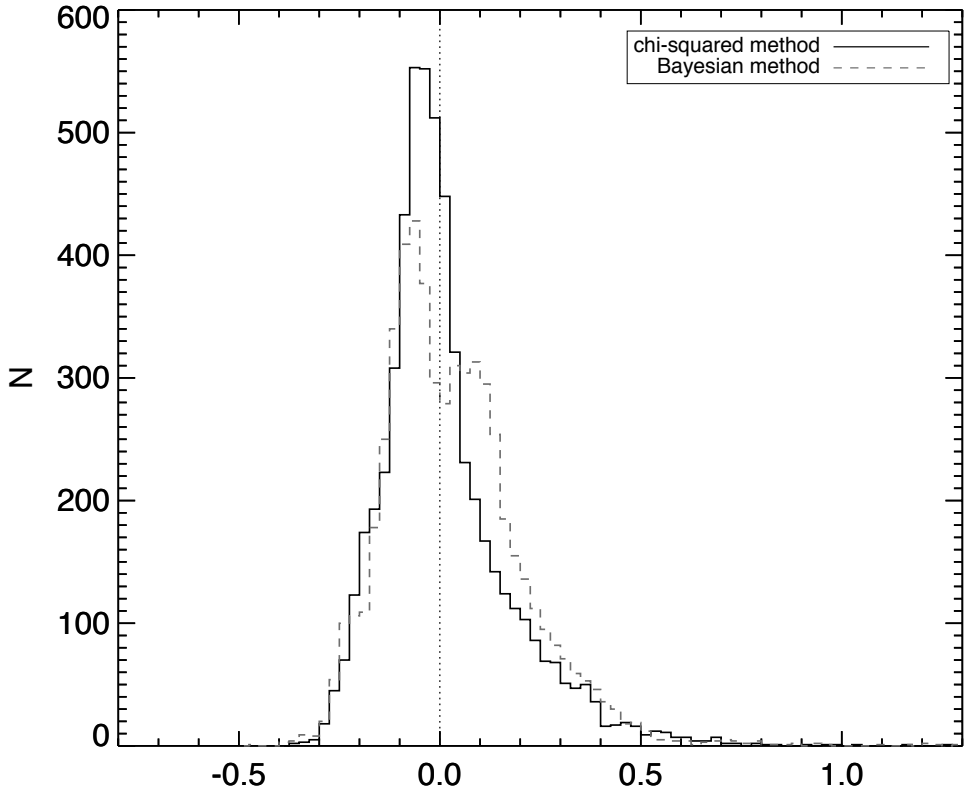
σ-clipped mean proper motions of QSOs/galaxies in 3x3-deg. bins

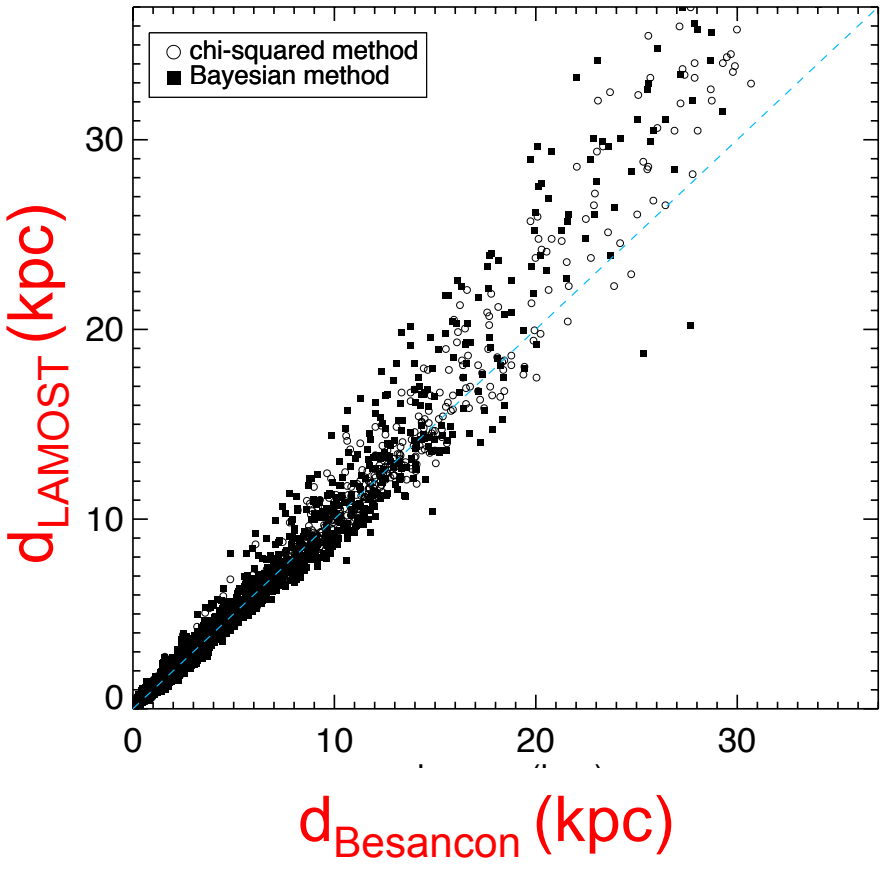
Grabowski, Carlin, Newberg, et al. 2015, RAA *accepted* (arXiv:1409.2890)



Distances to ~2 million stars using LAMOST stellar parameters:

- accurate to ~20% (with systematic offset for distant, metal-poor giants).
- Paper has been resubmitted (Carlin et al. 2015, AJ)…

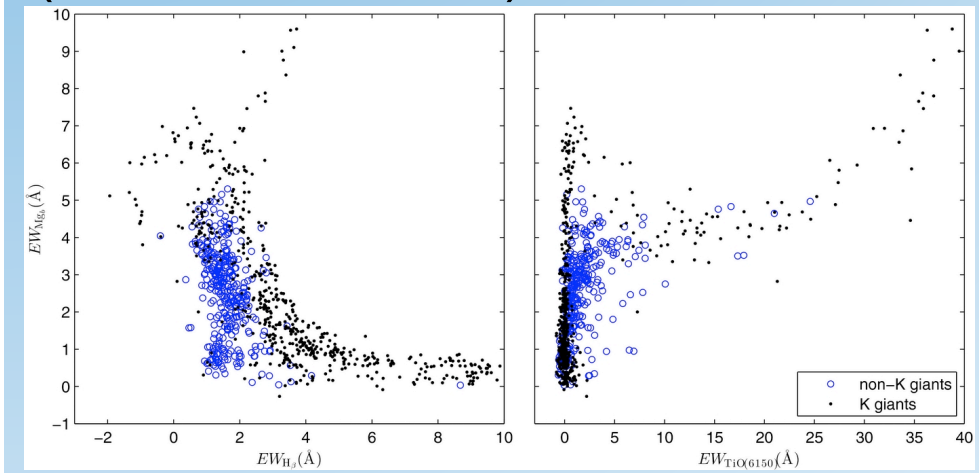


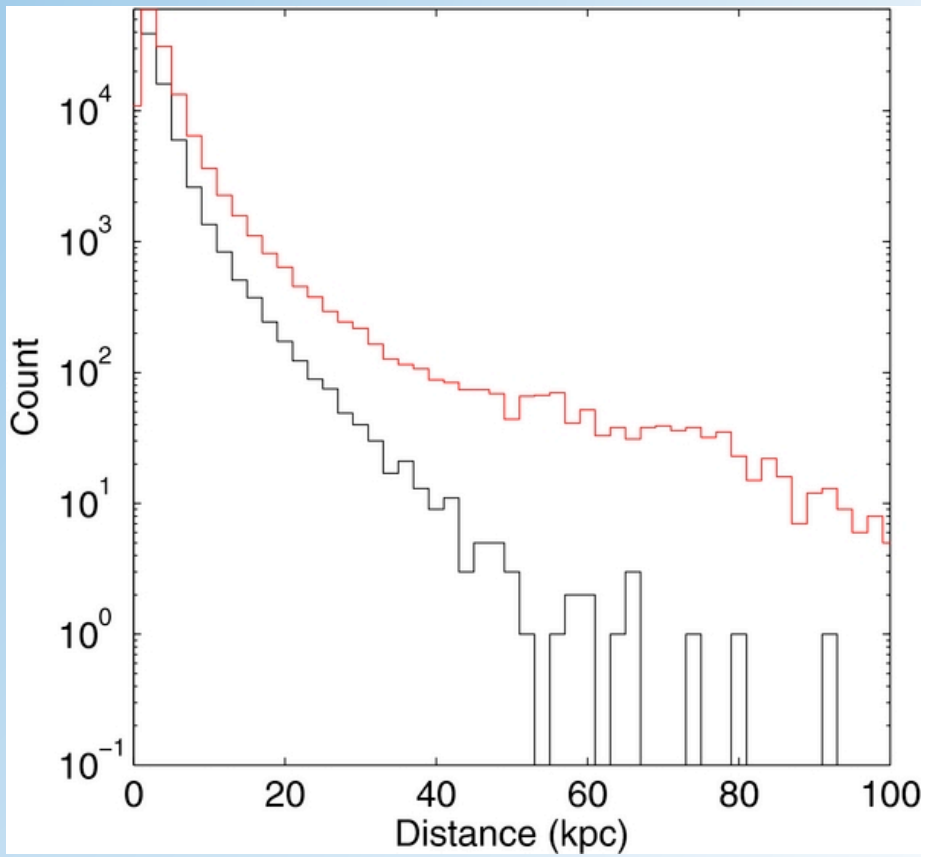


K-giant classification of LAMOST spectra (Liu, C., et al. 2014; ApJ 790, 110)

SVM-based classification, using primarily spectral indices (e.g., Mg b, TiO, Hβ)

- spectra with S/N as low as ~3
- ~290,000 K-giant candidates from DR1
- 80% completeness for S/N>20 (67% for S/N<20)



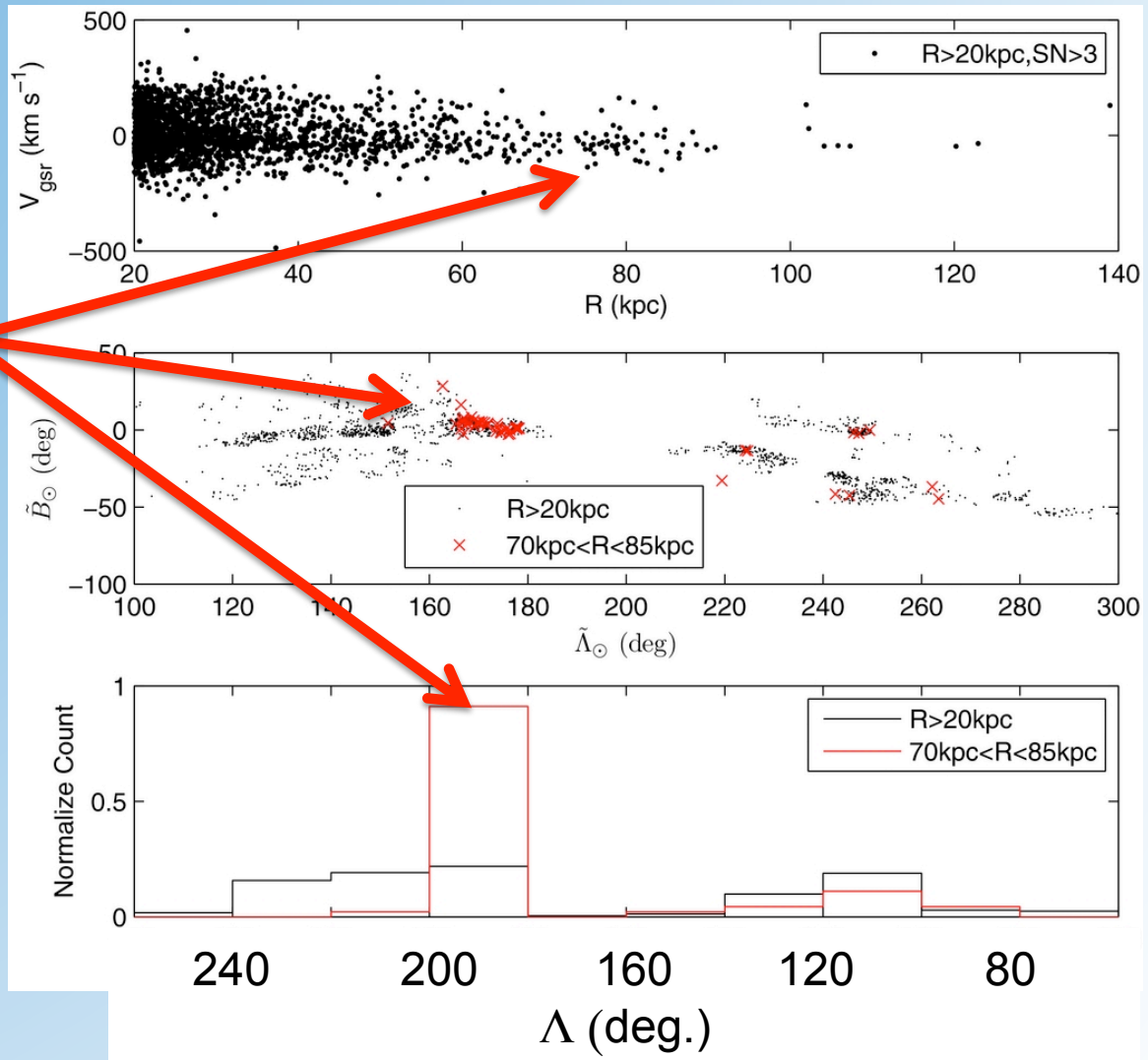


Black: giants identified via LAMOST stellar parameters

Red: K giants

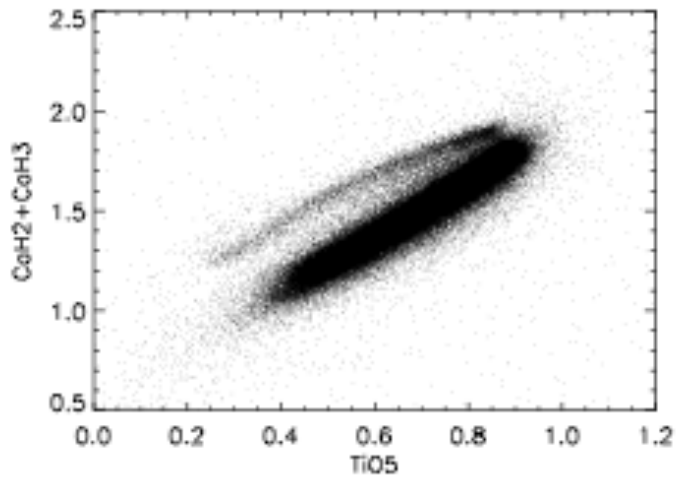
Sagittarius K-giants

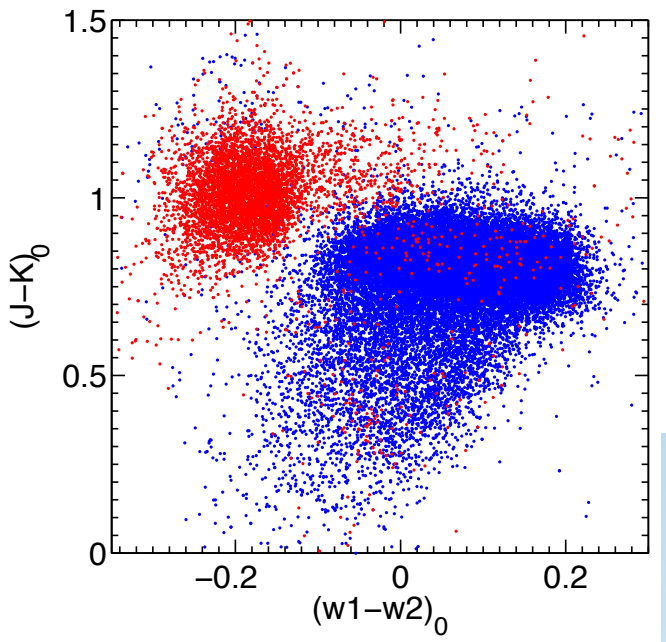
Large clump of stars at $70<R_{GC}<85$ kpc, $V_{gsr} \sim 0$ km/s, and B~0 deg., between $180 < \Lambda < 200$ deg.

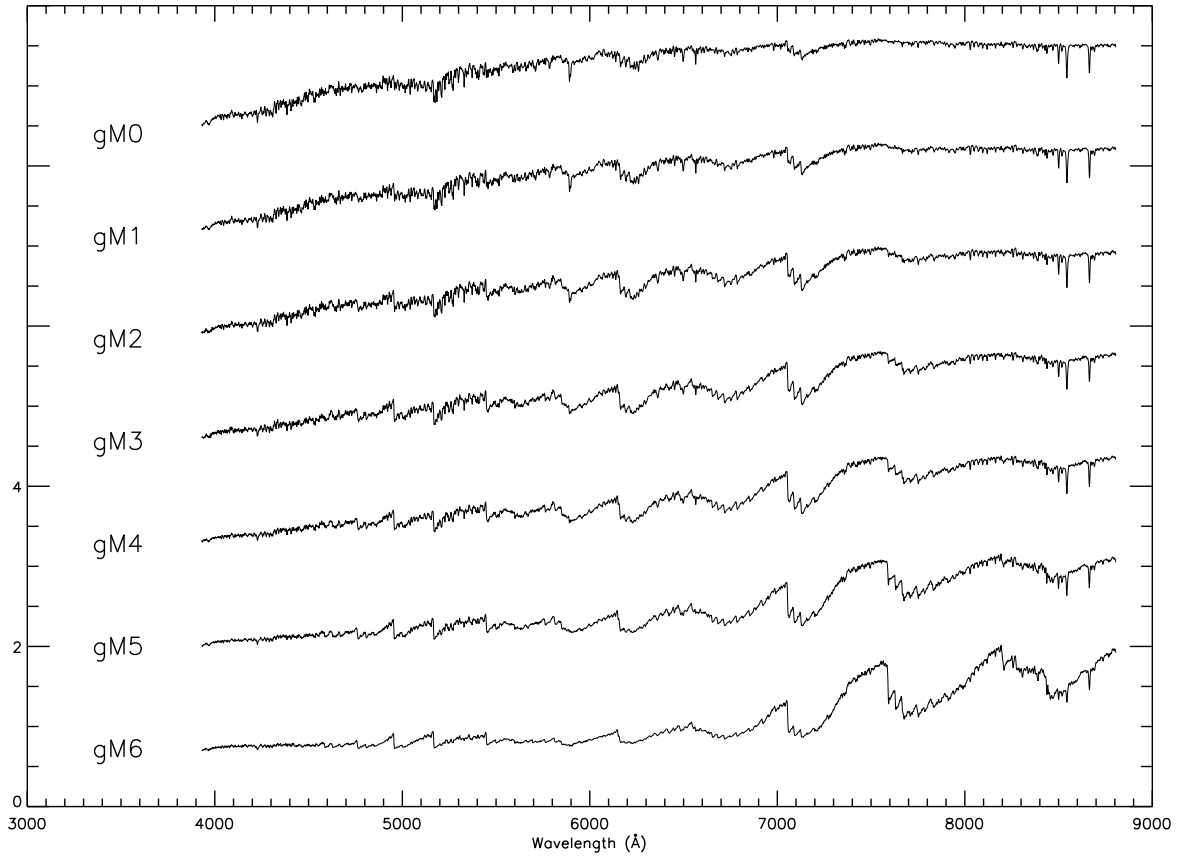


Liu, C., et al. 2014; ApJ 790, 110

M giants (spectroscopic selection)





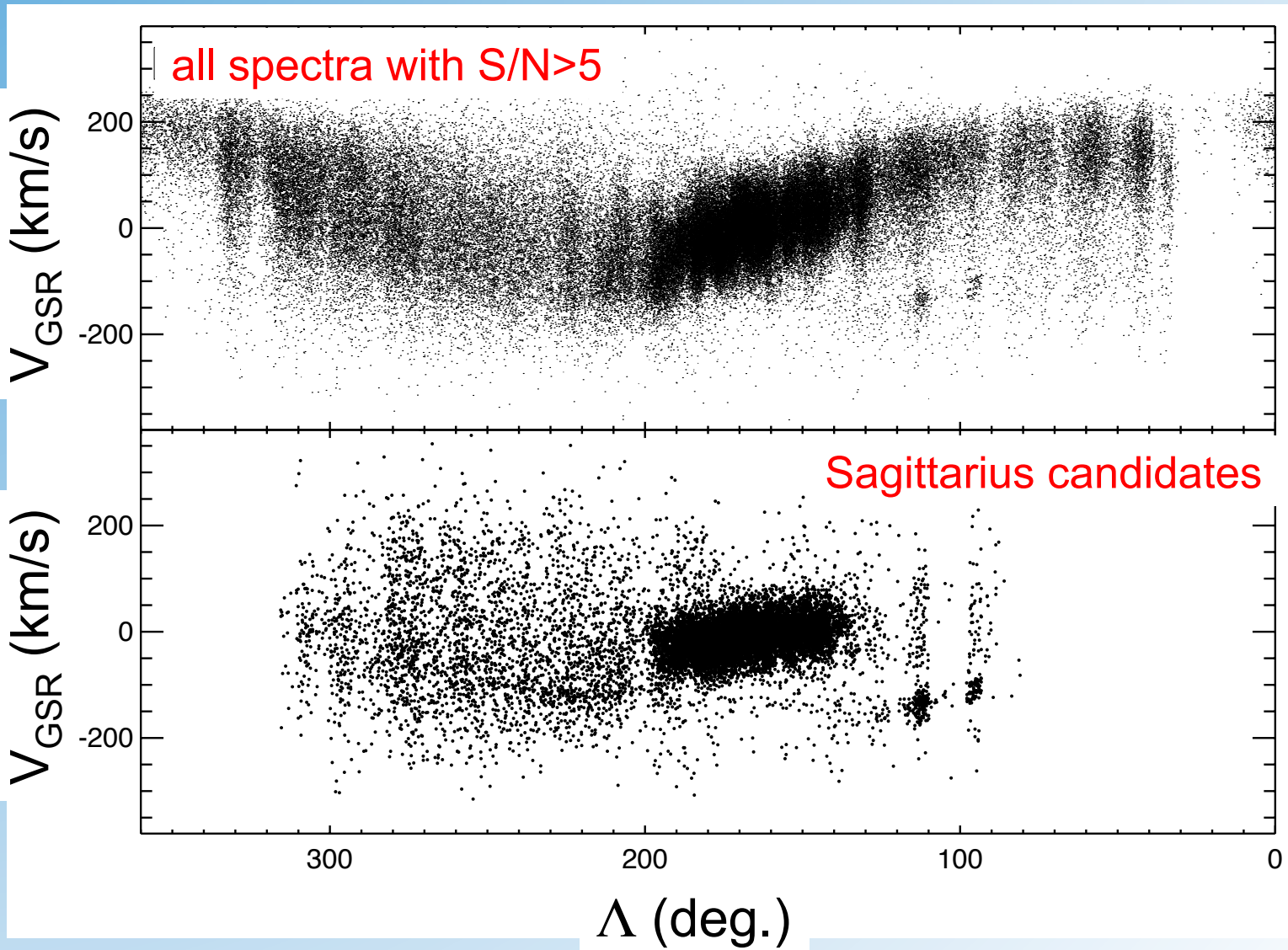


Zhong, J., et al. 2015 (RAA, submitted)

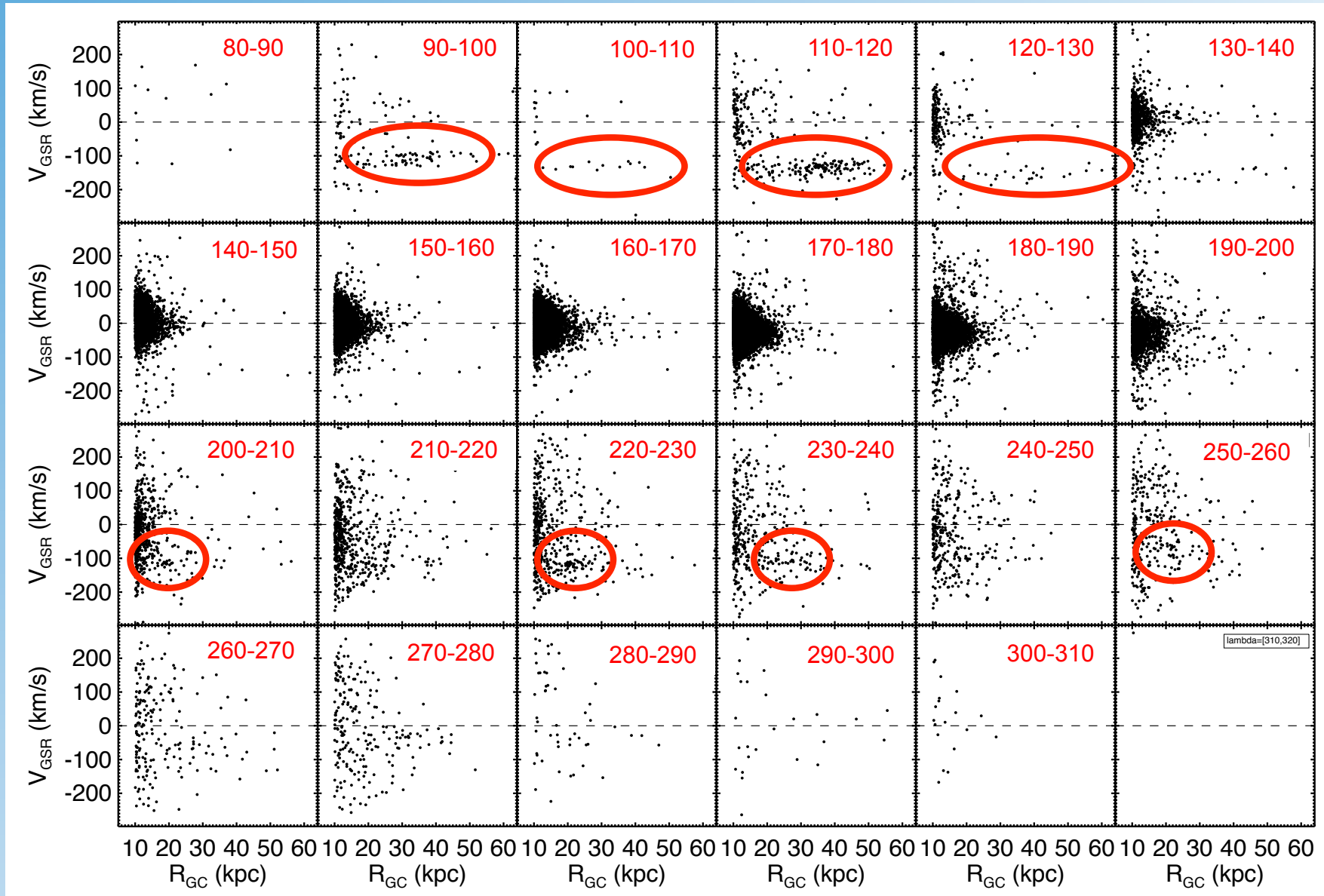
Galactic substructure with LAMOST

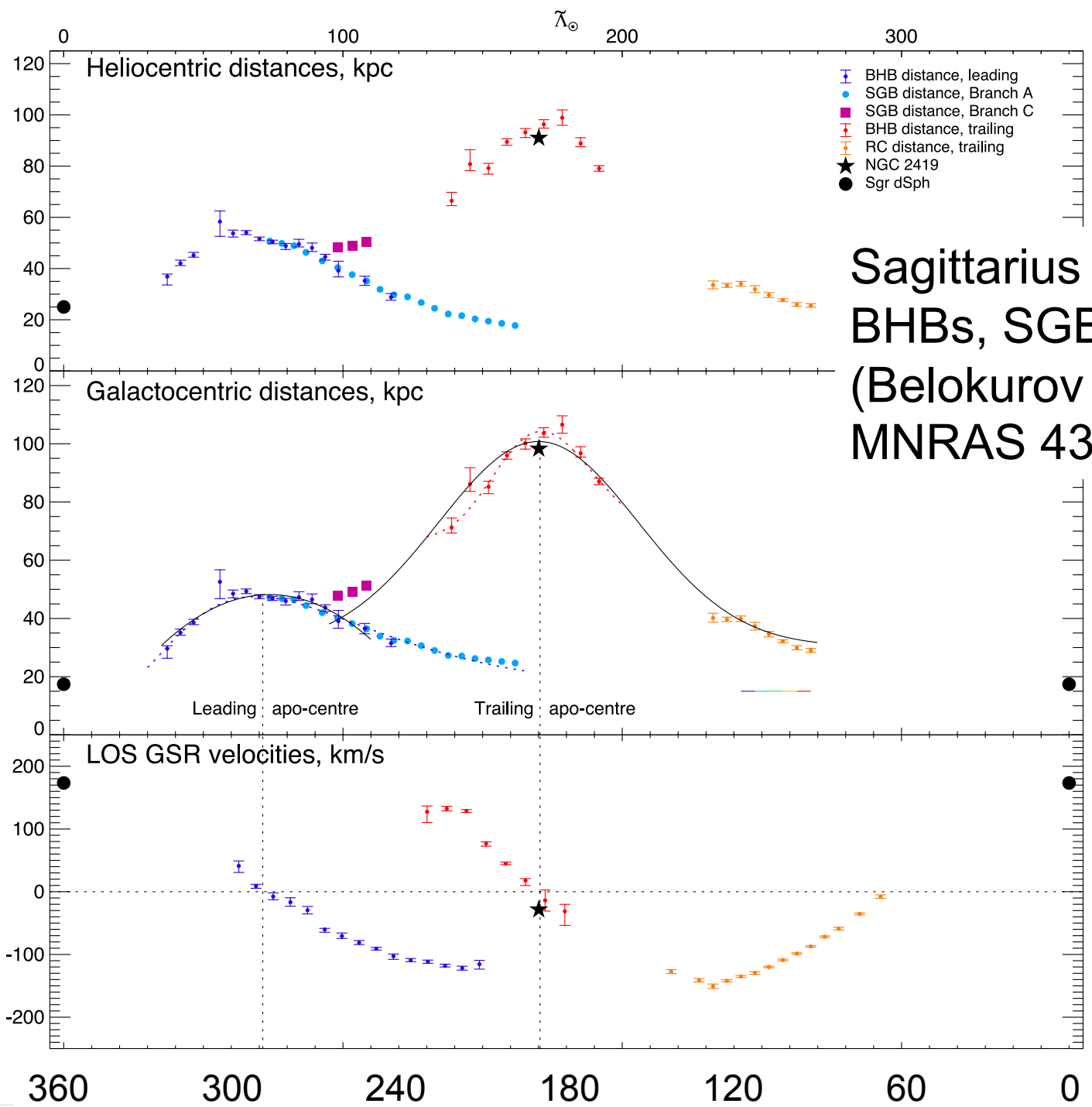
- Sagittarius stream
- Substructure with halo kinematics
- Disk velocity structures

LAMOST Sagittarius candidates: -1.8<[Fe/H]<-0.4, log g < 3.25, S/N > 5, |B| < 15 deg., dist > 5 kpc

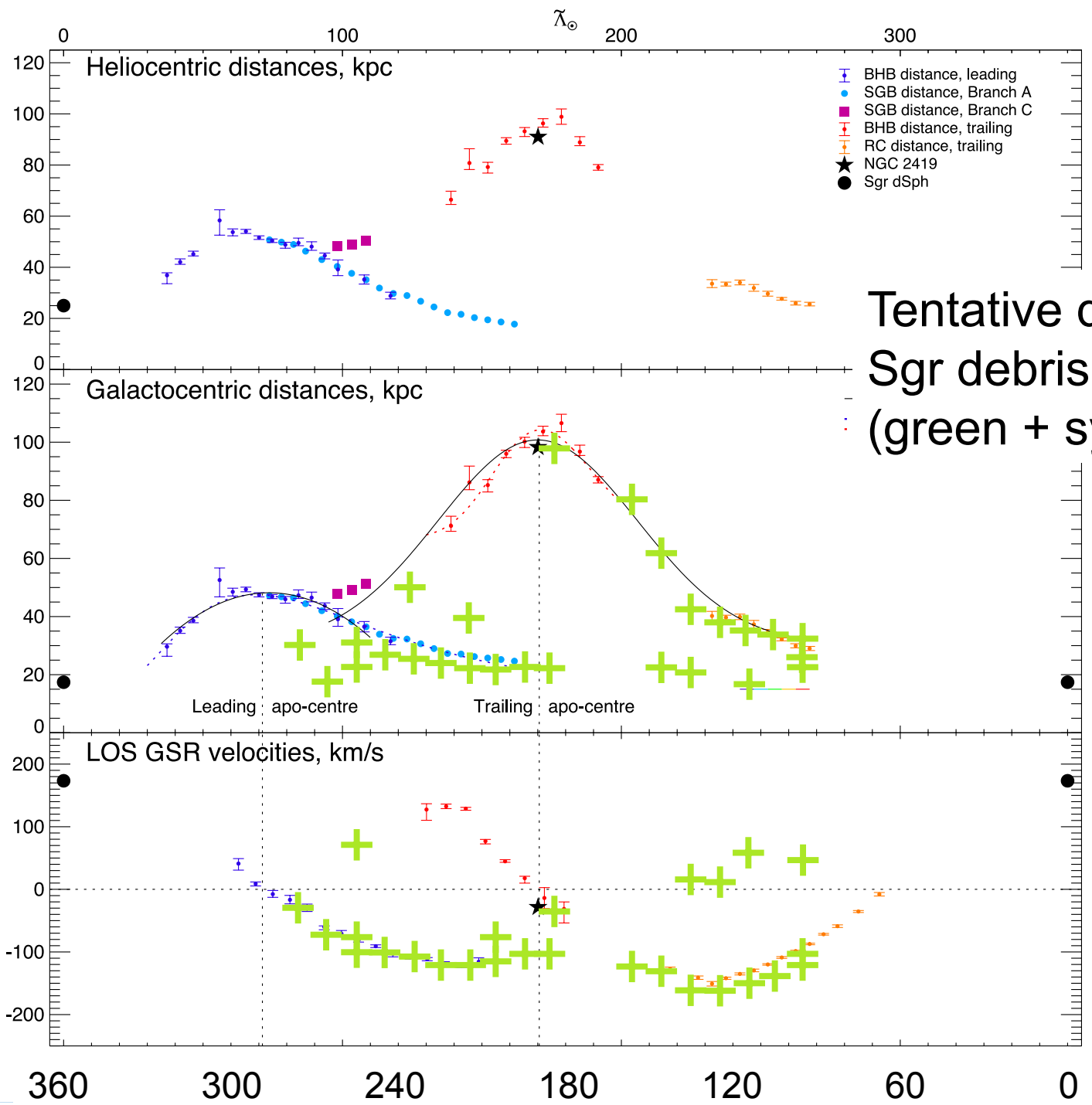


Sgr candidates split into 10-deg. ranges in Λ



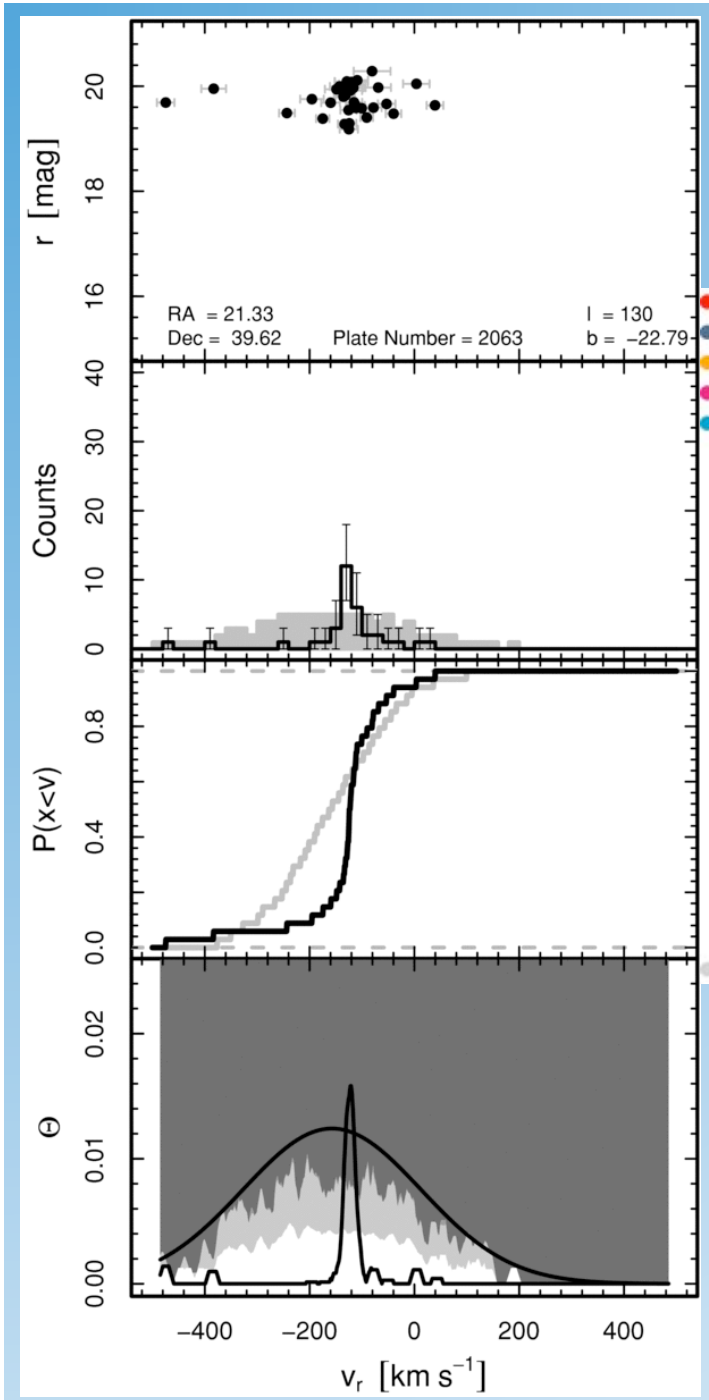


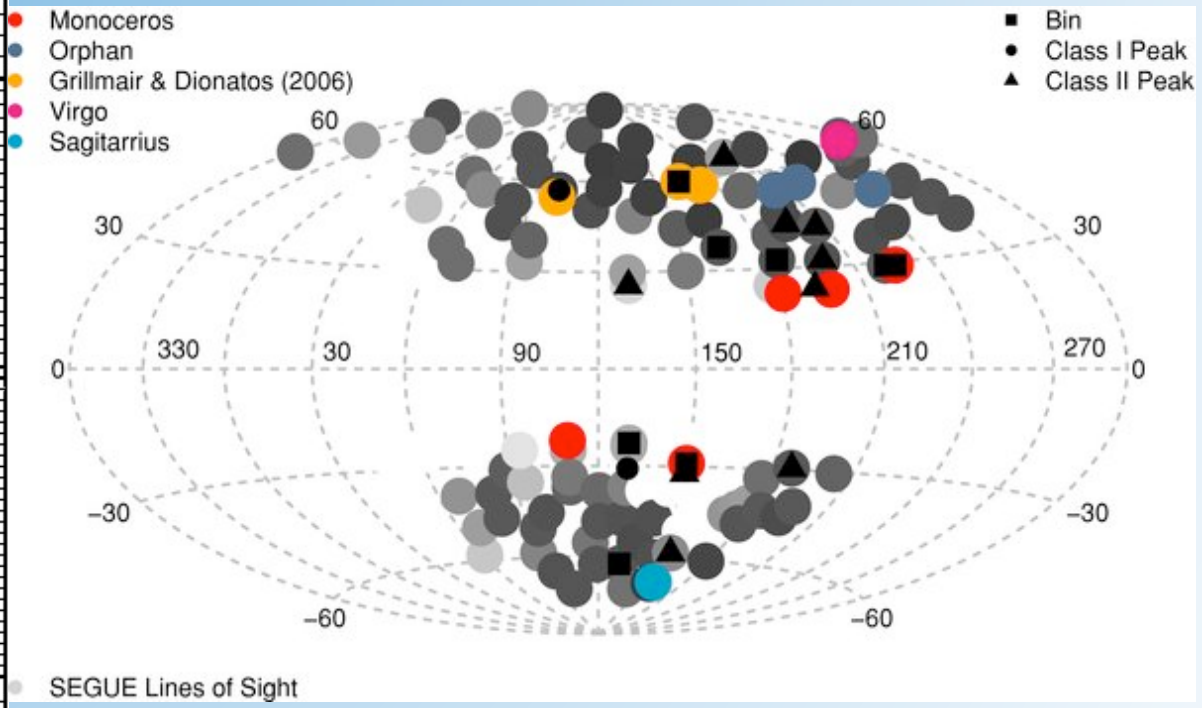
Sagittarius detections with BHBs, SGBs, RC stars (Belokurov et al. 2014, MNRAS 437, 116)



Tentative detections of Sgr debris from LAMOST (green + symbols)

Systematic search for velocity structures:

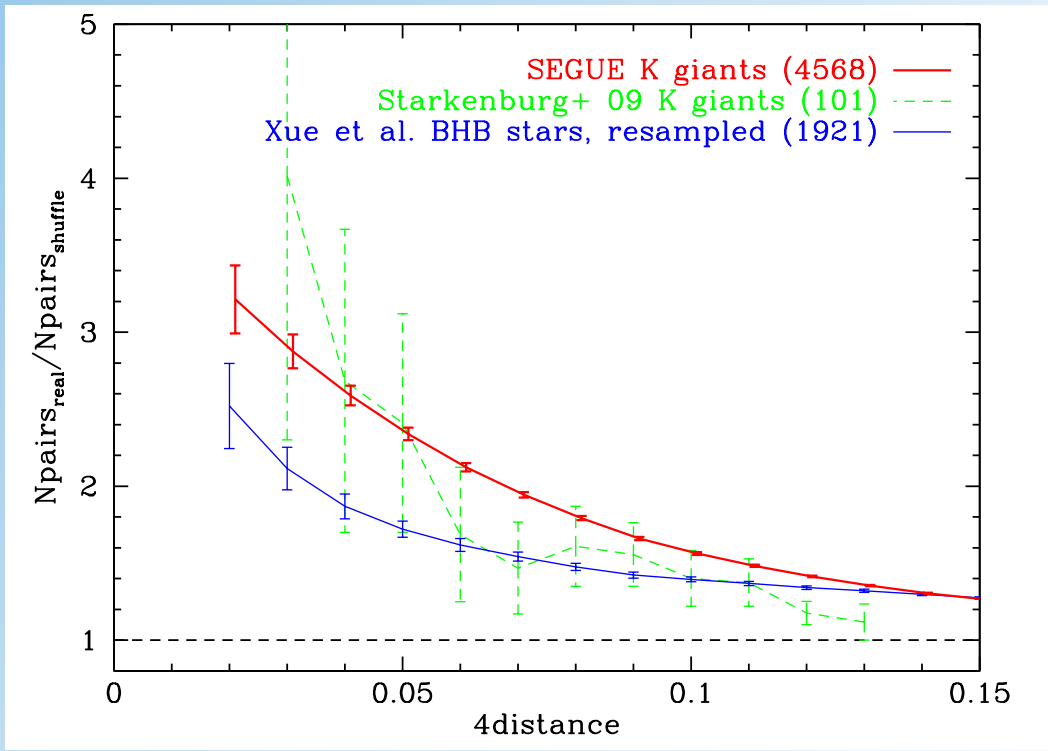




Elements of Cold HalO Substructure ("ECHOS");
Schlaufman et al. 2009 (ApJ 703, 2177)

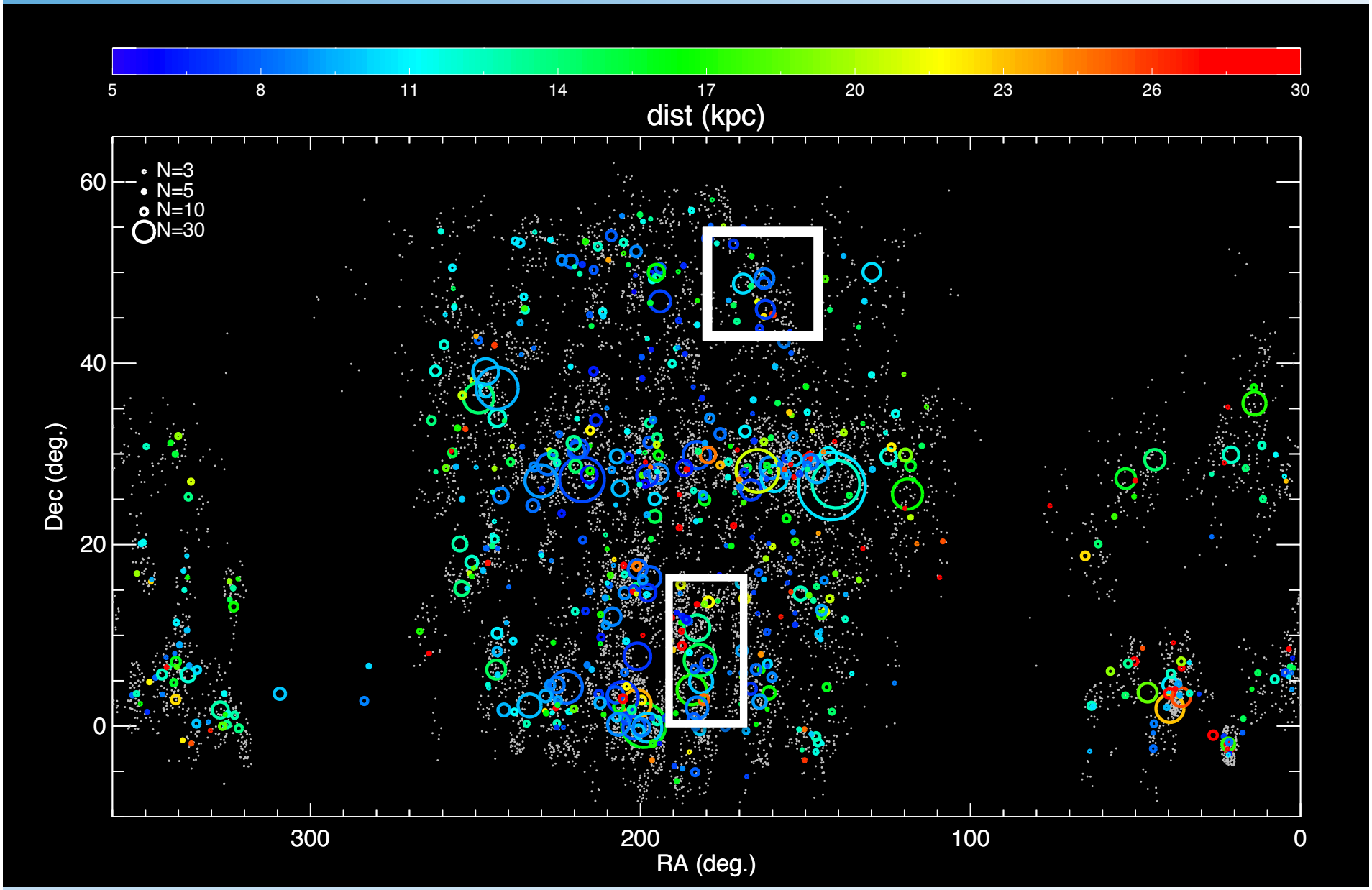
Finding clumps/associations of halo stars – the *4distance*

Idea: create a metric quantifying the separation of any two stars in (l, b, V_{GSR}, and distance) phase space



Starkenburg et al. 2009, ApJ, 698, 567
Janesh et al. 2015, arXiv: 1503.09133

LAMOST halo groups (linked via friends-of-friends algorithm) among ~8700 giants; Carlin et al. 2015 (*in prep*)



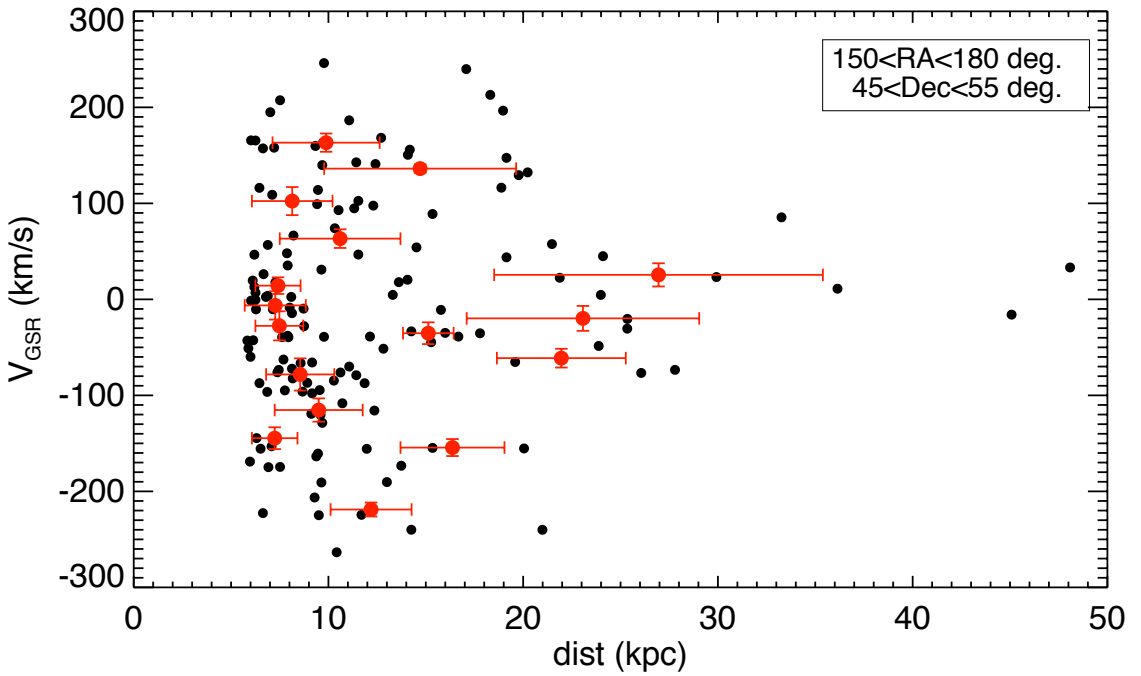
"random" regions:

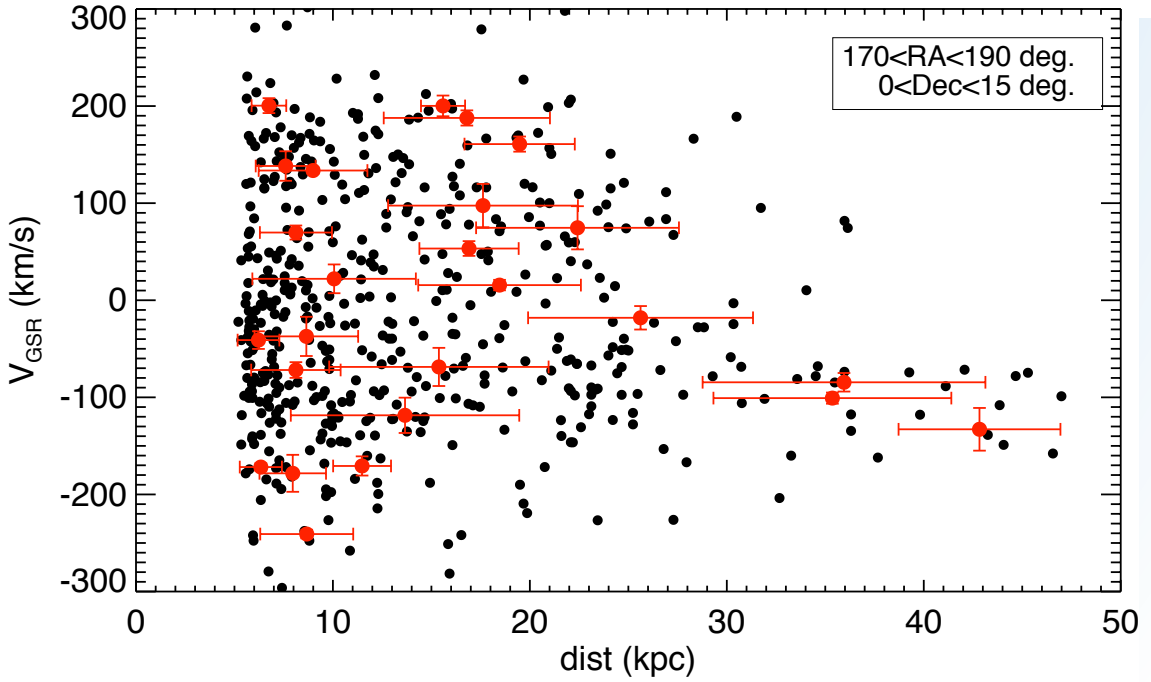
150 < RA < 180 deg.
45 < Dec < 55 deg.

16 groups with >3 members

170 < RA < 190 deg.
0 < Dec < 15 deg.

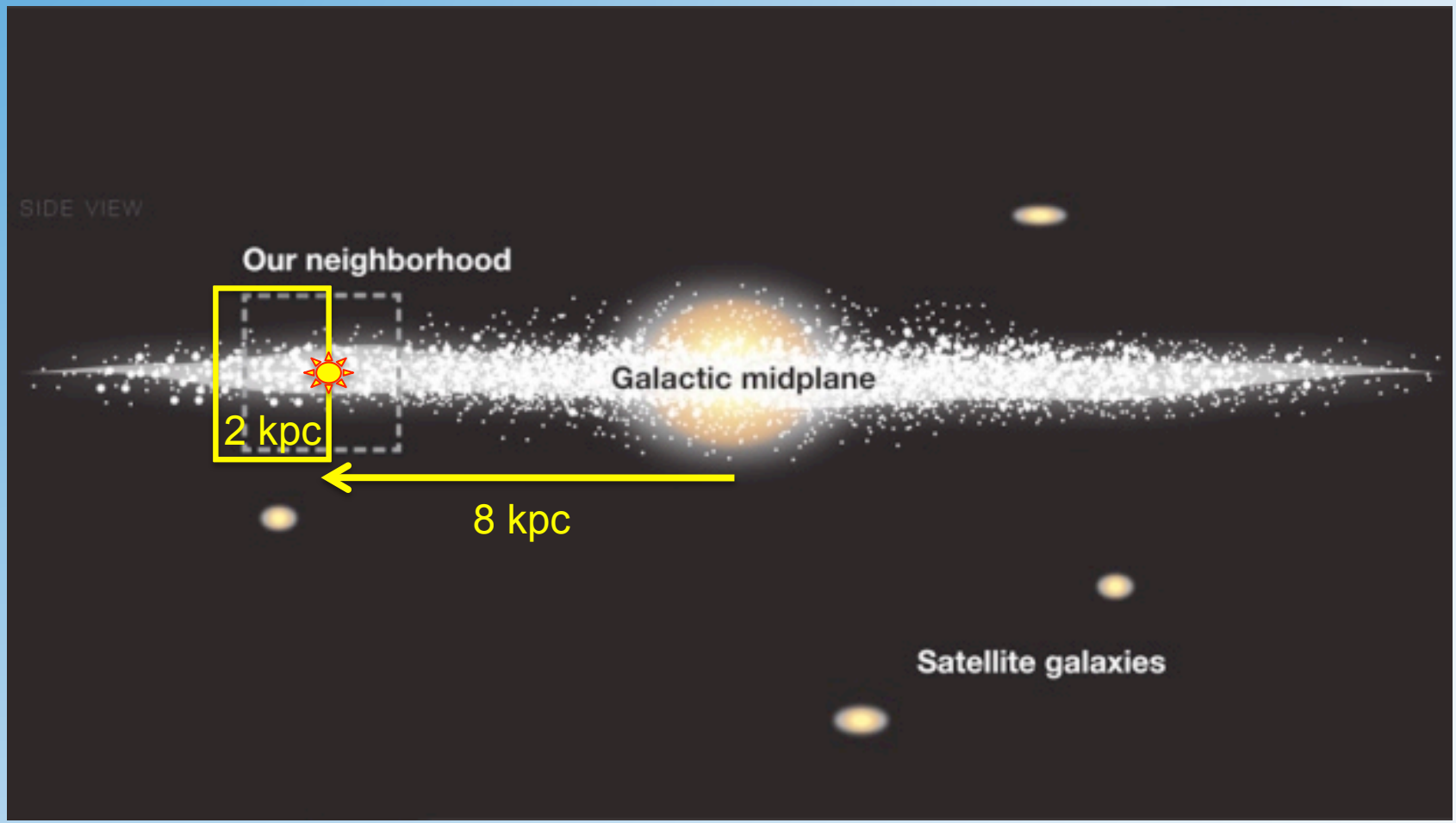
25 groups with >3 members





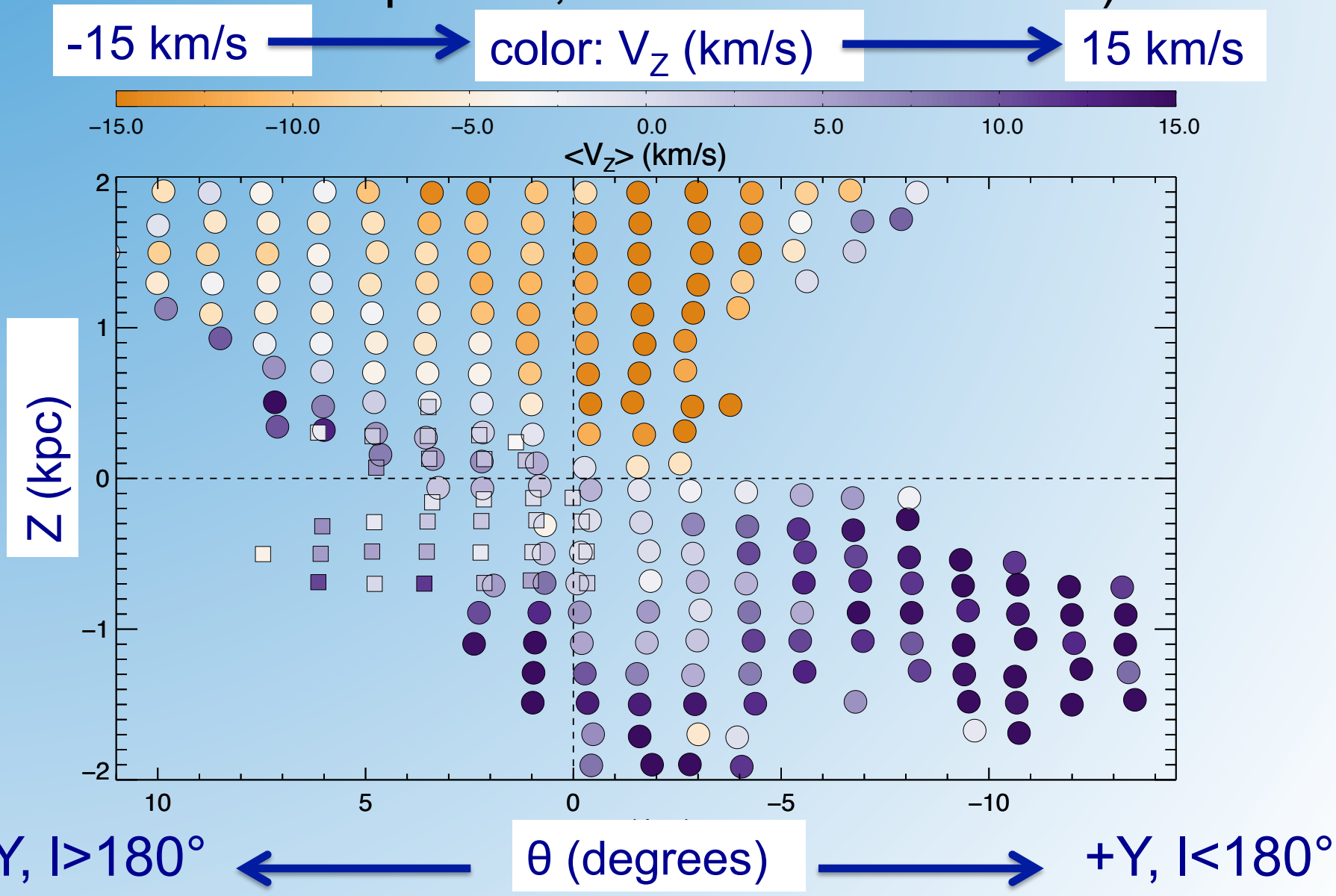
Effects of satellites on the Galaxy: “wiggles” in the disk

Carlin, DeLaunay, et al. 2013 (ApJL, 777, L5)

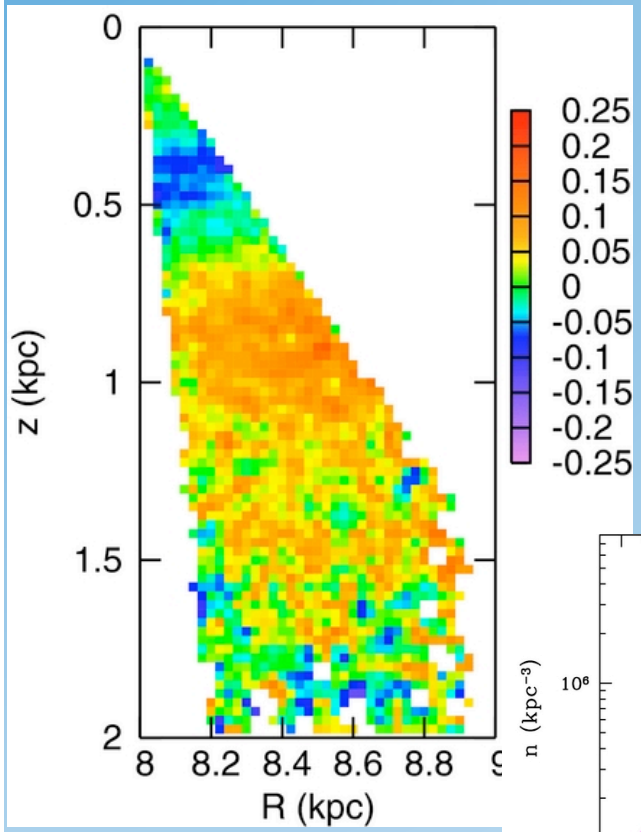


Kinematics of ~400,000 stars with LAMOST spectra, between $8 < R_{GC} < 10$ kpc (Sun at 8 kpc), $|Z| < 2$ kpc

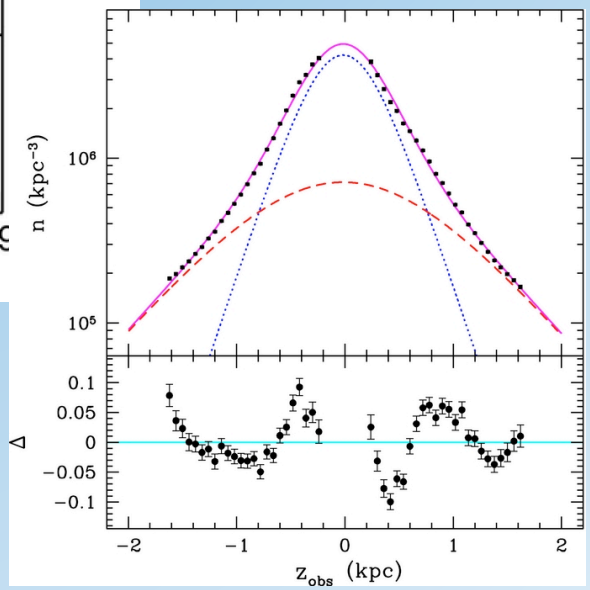
Bin stars in 200x200 pc bins, average the velocity (min. 50 stars per bin, but most have >1000)



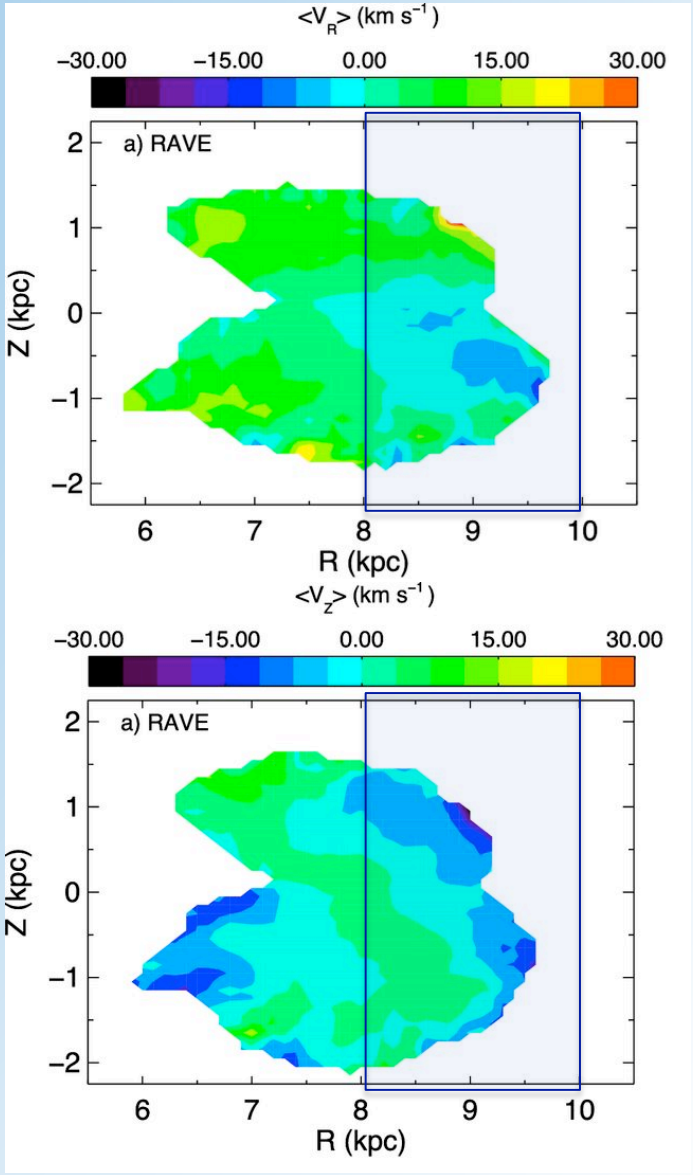
SDSS “waves”: Widrow et al. 2012 (ApJL 750, 41); Yanny & Gardner 2013 (ApJ 777, 91)

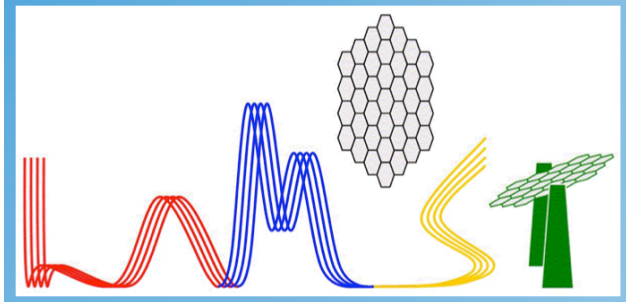


Vertical oscillations due to an external perturbation?



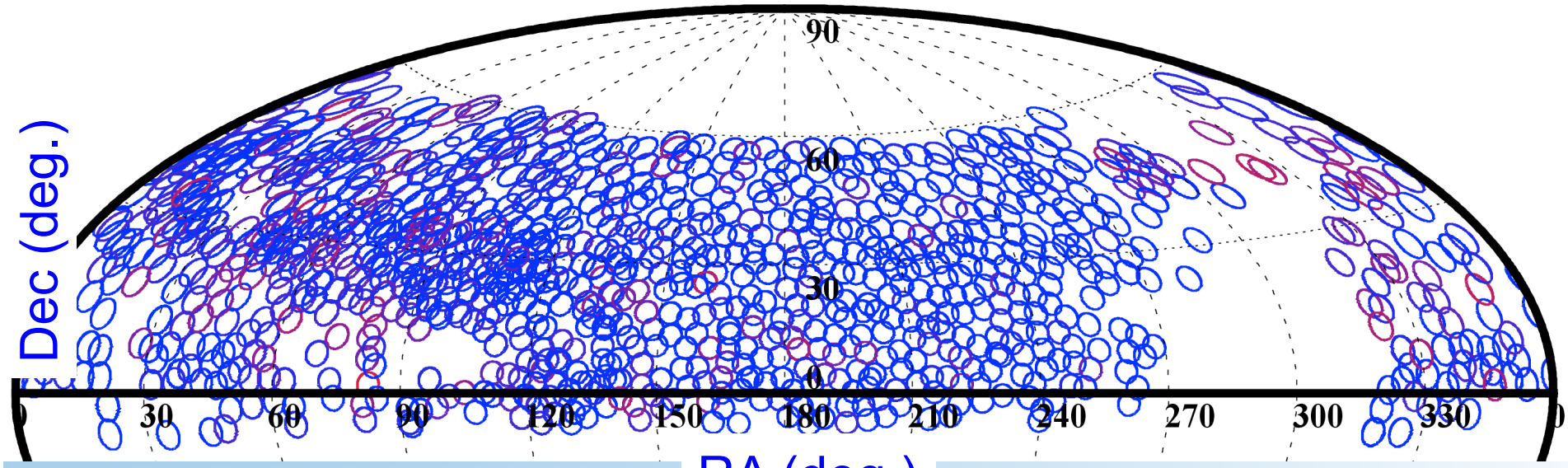
RAVE: Williams et al. 2013 (MNRAS 436, 101)





LAMOST: huge number of spectra, large contiguous sky coverage, SDSS-quality spectra

→ vast resource for kinematical substructure in the disk *and* halo



*** Look for “Tidal Streams in the Local Group and Beyond: Observations and Implications,” ed. H. Newberg & J. Carlin, published by Springer-Verlag, late 2015(?)