Scientific impact of the LAMOST regular surveys

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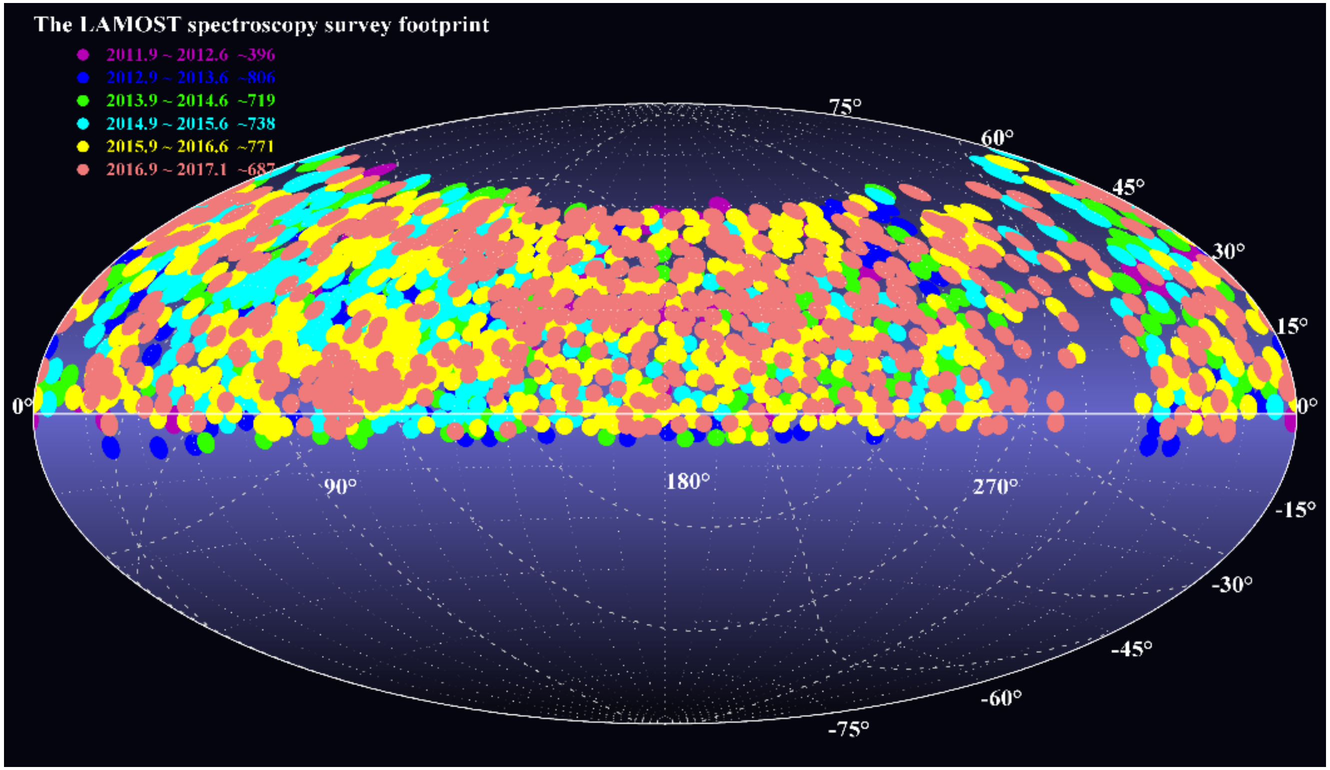
LAMOST timeline

- one of Chinese National Major Science Projects
  - Started in 1997
  - Finished in Aug. 2008
  - Checked and accepted by national government in June 2009
- Commissioning stage
  - June 2009 – Sept. 2011
- Pilot survey
  - Oct. 2011 - June 2012
- Regular survey
  - Sep. 2012 – June 2017

Survey progress and data products



Data set	Ending date	No. of spectra	No. of stellar spectra	Spectra of SNR > 10	No. of spectra with parameters	Release/Public date
DR0	20120617	958,944	812,911	619,151	396,249	2012.08/2012.08
DR1	20130603	2,660,613	2,342,849	1,925,735	1,127,872	2013.09/2015.03
DR2	20140603	4,309,098	3,843,851	3,293,600	2,174,812	2014.12/2016.07
DR3	20150602	5,968,162	5,354,883	4,665,075	3,185,475	2015.12/2017.07
DR4	20160602	7,681,185	6,898,298	6,076,210	4,202,127	2016.12/2018.07
DR5	20170615	9,000,000		7,360,000	5,110,000	2017.12/2019.07

LAMOST Sciences

- Proposed (1996)
  - Extra-galactic spectroscopic survey
    - Galaxy & QSO redshift survey
  - Stellar spectroscopic survey
    - Structure of the Galaxy & stellar physics
  - Cross identification of multi-waveband survey

- Present (2012)
  - 2/3 slits : R = 500 ➔ 1800
  - r < 17.8m (SDSS: 17.5m)

- Sciences
  - Galactic survey
    - Structure & evolution of the Galaxy
    - Stellar physics
  - QSO & galaxy
  - Cross identification of multi-waveband survey

LAMOST Experiment for Galactic Understanding and Exploration (LEGUE)

Science goals (2012) LEGUE RAA mini-volume

1. Extremely metal poor star candidates, MDF
2. Kinematic/chemical features of the thin/thick disk stars, mass distribution
3. A thorough analysis of the disk/spheroid interface at GAC ✪
4. Moving groups, know structures ✪
5. Survey of OCs
6. Hypervelocity stars
7. Survey of OB stars, 3D extinctions
8. Census of young stellar objects in the plane

Dynamics of the Milky Way

Mass of the Milky Way

- Hitherto the most accurate Galactic rotation curve extending to 100 kpc based on 12000 selected from LSS-GAC DR2 and 4000 selected from APOGEE low Galactic latitude ($|b| < 3^o$) primary red clump stars, and 6000 halo K giants selected from SDSS

Huang et al. 2016, MN, 463, 2623

$$\mathbf{M_{Vir} = (0.90 \pm 0.08) \times 10^{12}\ M_\odot}$$

- Measurements of the Galactic escape velocities at Galactocentric radii between 5 and 14 are presented based on a sample of 527 high velocity halo stars ($|v_r| > 300$ km/s, [Fe/H] < -1) selected from the LAMOST Galactic spectroscopic surveys

Huang et al. 2017, in prep.

$$\mathbf{M_{Vir} = (0.92 \pm 0.06) \times 10^{12}\ M_\odot}$$

- Mass profile from LAMOST+SDSS halo K-giants with galactocentric radius of 16-85 kpc

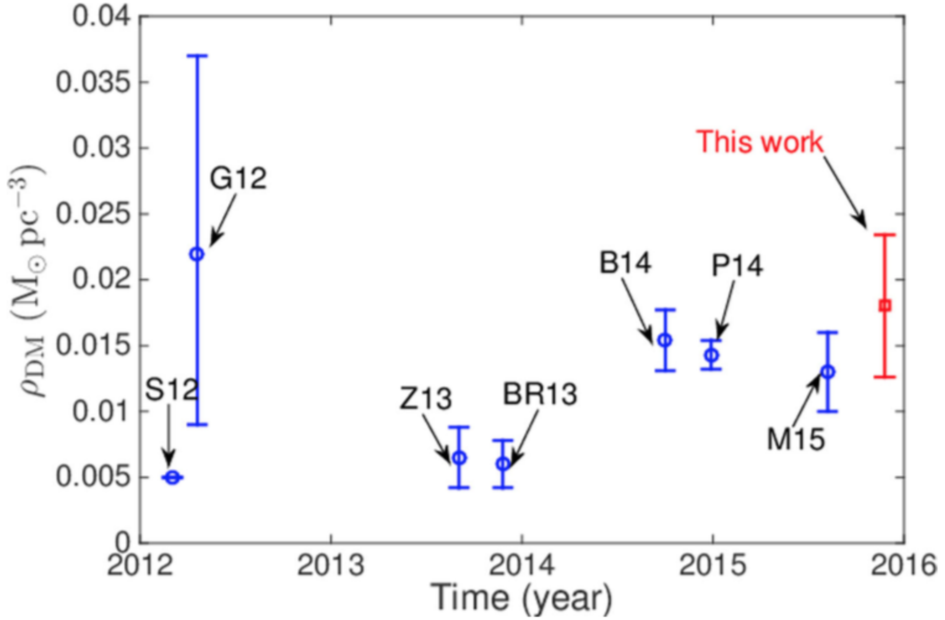
Liu et al. 2017, in prep.

$$\mathbf{M_{Vir} = 0.9\ (+0.6, -0.3) \times 10^{12}\ M_\odot}$$

Dark matter mass density in the solar neighborhood

Xia, Liu, et al., MNRAS,2

- With LAMOST data and a simple analytical Kz force model depending on less assumptions
- the volume density of the dark matter around us is $0.018 \pm 0.005 M_{\odot} pc^{-3}$



Huang et al.

ρ_{DM} = 0.32(+0.02, −0.02) GeV cm^{-3} = $0.0084 \pm 0.0005 M_{\odot} pc^{-3}$

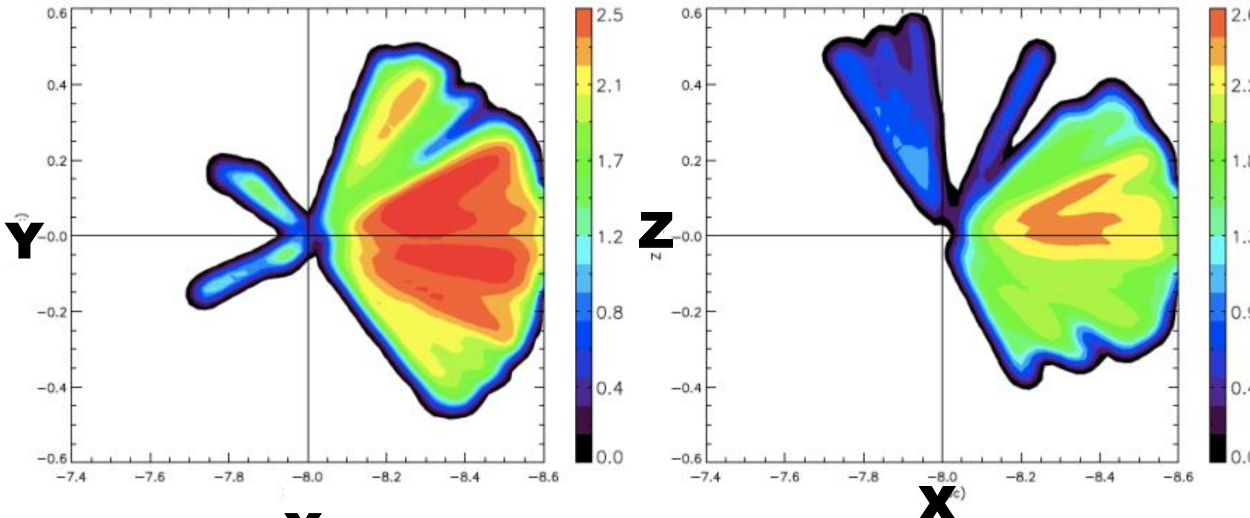
ρ_{DM} = 0.33 ± 0.02 GeV cm^{-3} = $0.0087 \pm 0.0005 M_{\odot} pc^{-3}$

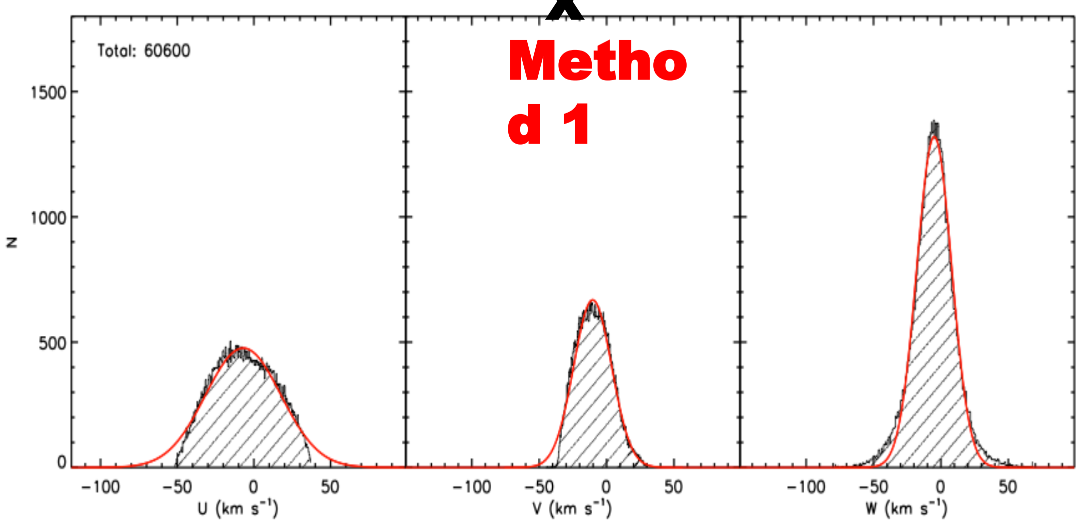
The Local Standard of Rest

Based on 94,332 thin disk FGK dwarfs within 600 pc of the Sun.

Result: (7.0±0.2,10.1±0.1,5.0±0.1) km/s

Huang et al. 2015, MNRAS, 449, 162





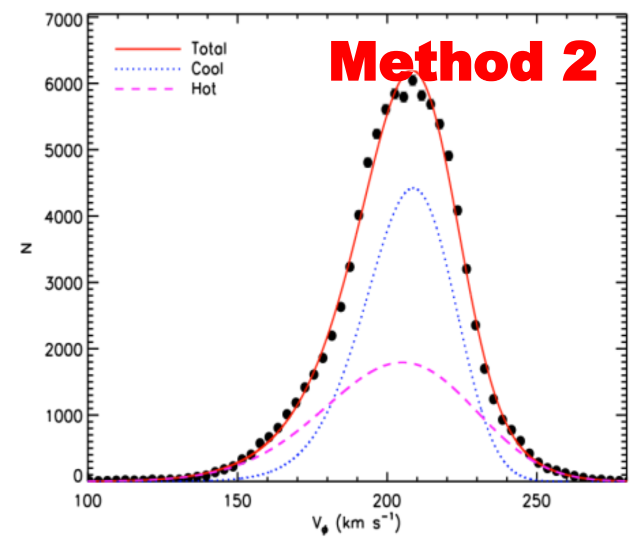


Table 1. Measurements of the LSR in the literatures and from the current work

Source	Data	$U_\odot$ (km s^{-1})	$V_\odot$ (km s^{-1})	$W_\odot$ (km s^{-1})
This study (2014)	LSS-GAC DR1	7.01±0.20	10.13±0.12	4.95±0.09
Bobylev & Bajkova (2014)	Young objects	6.00±0.50	10.60±0.80	6.50±0.30
Coşkunoğlu et al. (2011)	RAVE DR3	8.50±0.29	13.38±0.43	6.49±0.26
Bobylev & Bajkova (2010)	Masers	5.50±2.2	11.00±1.70	8.50±1.20
Breddels et al. (2010)	RAVE DR2	12.00±0.60	20.40±0.50	7.80±0.30
Schönrich et al. (2010)	Hipparcos	$11.10^{+0.69}_{-0.75}$	$12.24^{+0.47}_{-0.47}$	$7.25^{+0.37}_{-0.36}$
Reid et al. (2009)	Masers	9.0	20	10
Francis & Anderson (2009)	Hipparcos	7.50±1.00	13.50±0.30	6.80±0.10
Bobylev & Bajkova (2007)	F & G dwarfs	8.70±0.50	6.20±2.22	7.20±0.80
Piskunov et al. (2006)	Open clusters	9.44±1.14	11.90±0.72	7.20±0.42
Mignard (2000)	K0-K5	9.88	14.19	7.76
Dehnen & Binney (1998)	Hipparcos	10.00 ±0.36	5.25±0.62	7.17±0.38
Binney et al. (1997)	Stars near South Celestial Pole	11.00±0.60	5.30±1.70	7.00±0.60
Mihalas & Binney (1981)	Galactic Astronomy (2nd Ed.)	9.00	12.00	7.0
Homann (1886)	Solar neighborhood stars	17.40±11.2	16.90±10.90	3.60±2.30

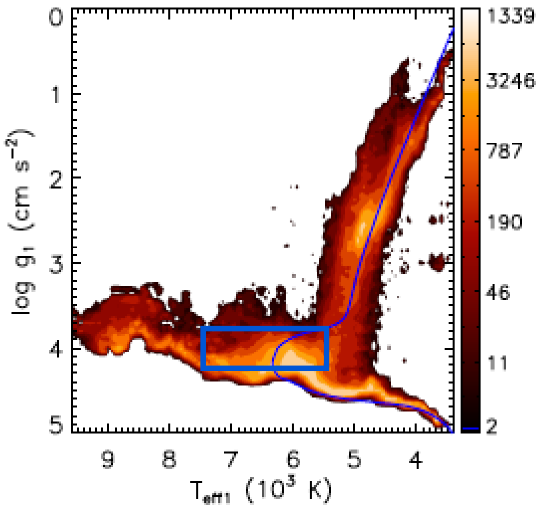
- **Highest accuracy of (U, V, W)**
- **V is 2 times of one in “Galactic Dynamics” (Dehnen & Binney 1998)**

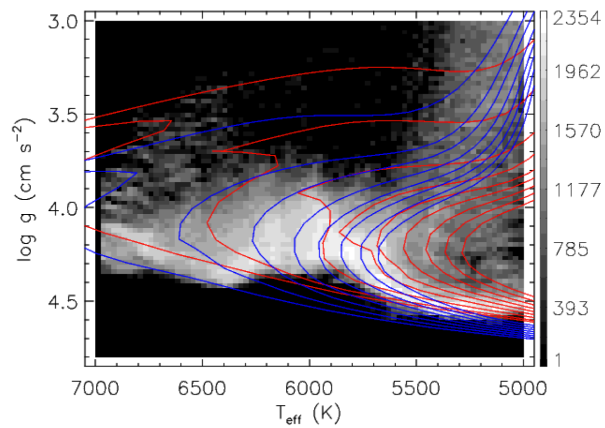
Composition, kinematics of stellar populations

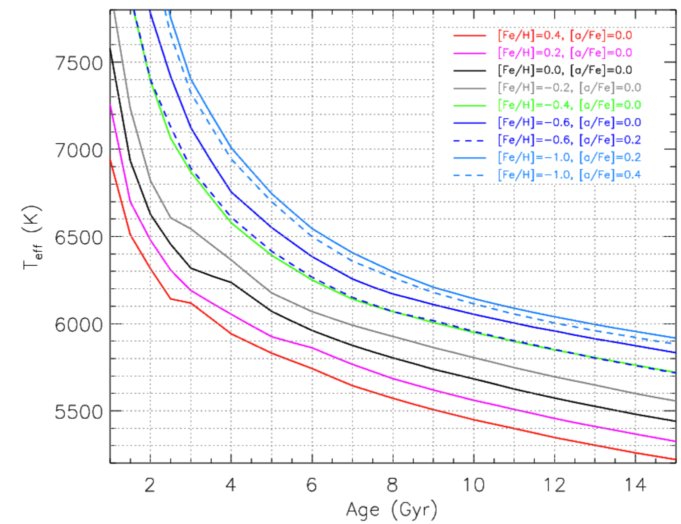
Metallicity gradients of the Galactic disk

Xiang et al. 2015, RAA, 15, 1209

- Metallicity: Fossil record of star formation and chemical enrichment
- [M/H](r, v, t) encodes the assemblage history of the Galactic disk
- Metallicity gradients [Fe/H](r) measured using a variety of tracers: OCs; Cepheids; H II regions; FGK stars; Red giants; Red clump stars; PNe
- Few measurements available of the temporal variations of metallicity gradients







- 300,000 turn-off stars selected from the LSS-GAC DR2 (Xiang et al. 2015, in prep.)
- Stellar ages derived by matching with the isochrones (Y2)
- Uncertainties of age (~30%) and distance (~20%) estimated by Monte-Carlo simulations

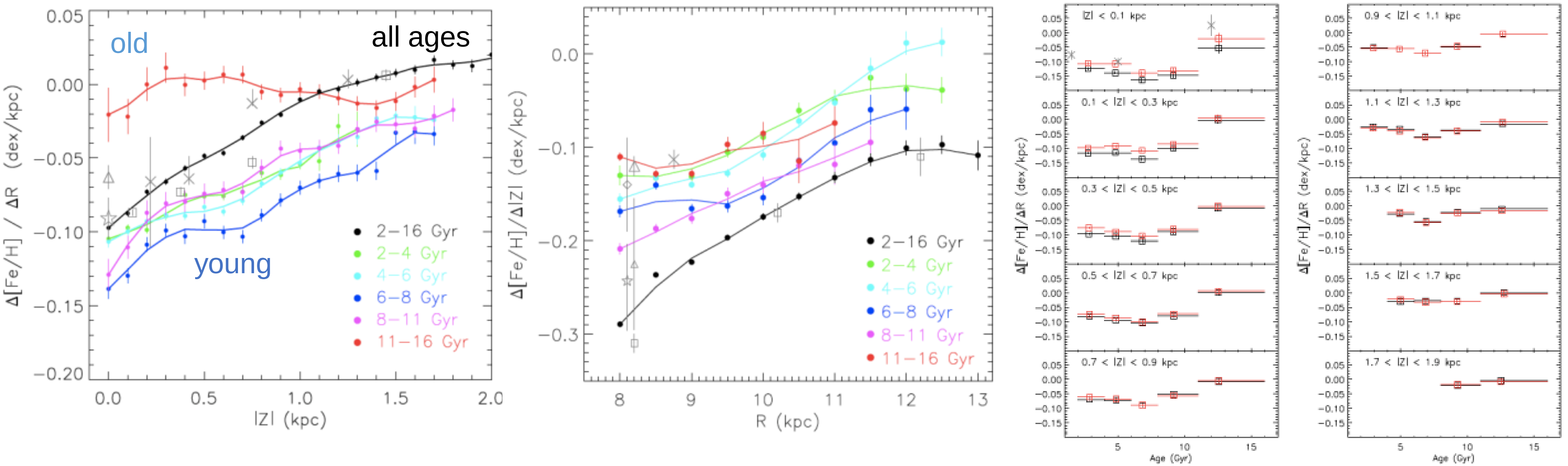
Age-dependent metallicity gradients

Xiang et al. 2015, RAA, 15, 1209

Radial gradients as a function of disk height |Z| for stars of different ages

Vertical gradients as a function of radius |R| for stars of different ages

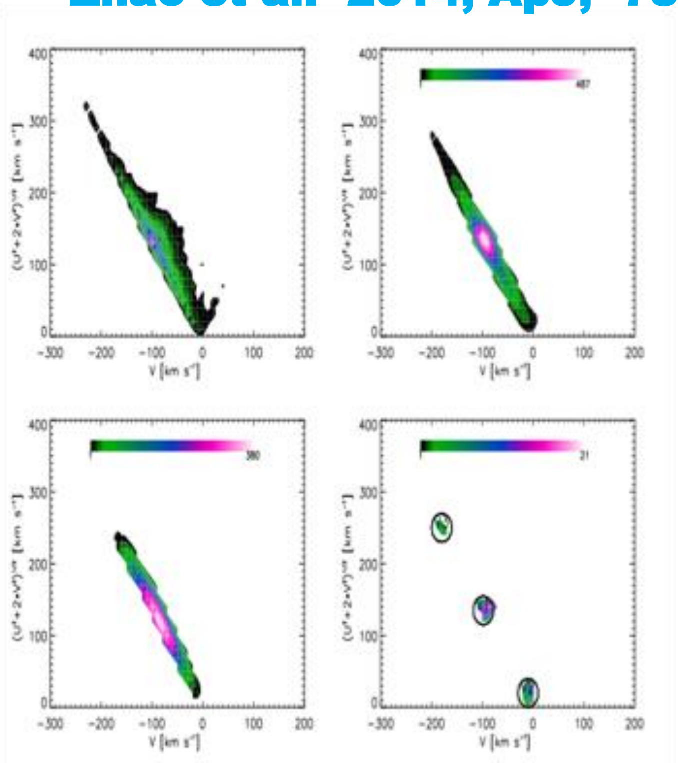
Radial gradients as a function of age for stars at different height |Z|



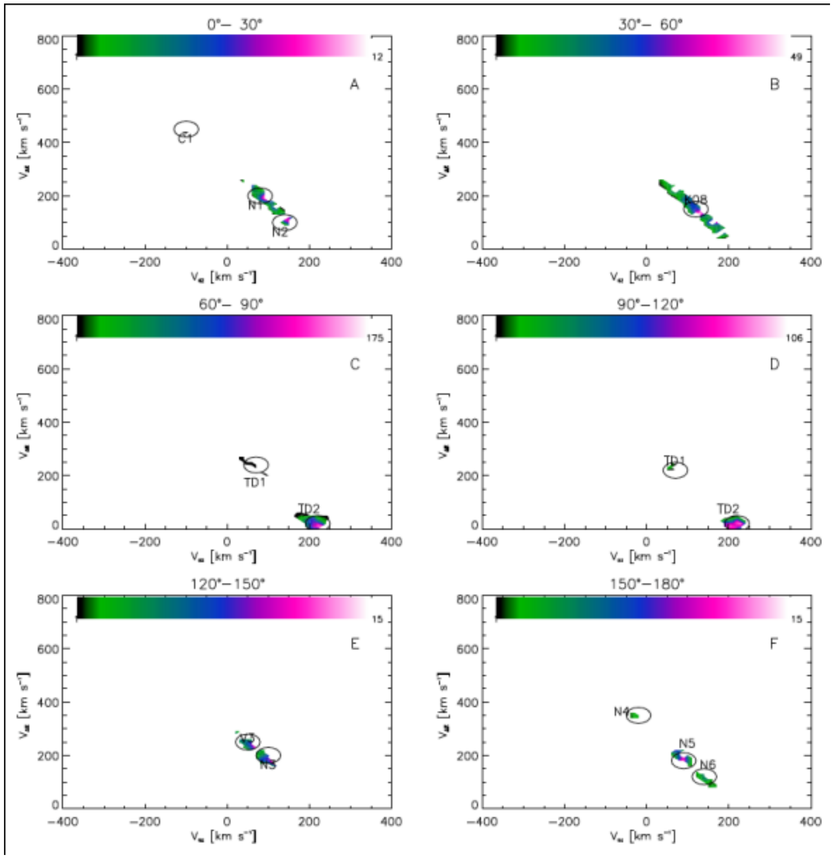
- Radial gradients show significant temporal variations. The oldest stars have zero gradients at all heights. Younger stars have negative gradients that steepen with decreasing height. The gradients are steepest at ages between 7-8 Gyr
- Stars of all ages show (negative) vertical gradients. Stars of oldest ages have nearly constant gradients at different radii. For younger stars, the (negative) gradients steepen with decreasing radius
- The disk assemblage may have experienced two phases, corresponding to the thick and thin disk formation
- The presence of vertical gradients do not support the thick disk formation scenario by fast, highly-turbulent gas-rich merger as proposed by Brook et al. (2004, 2005), but favor a slow, pressure-supported gas collapse following the formation of an extreme Population II system proposed by Gilmore et al. (1989)

Moving Groups

Zhao et al. 2014, ApJ, 787, 31

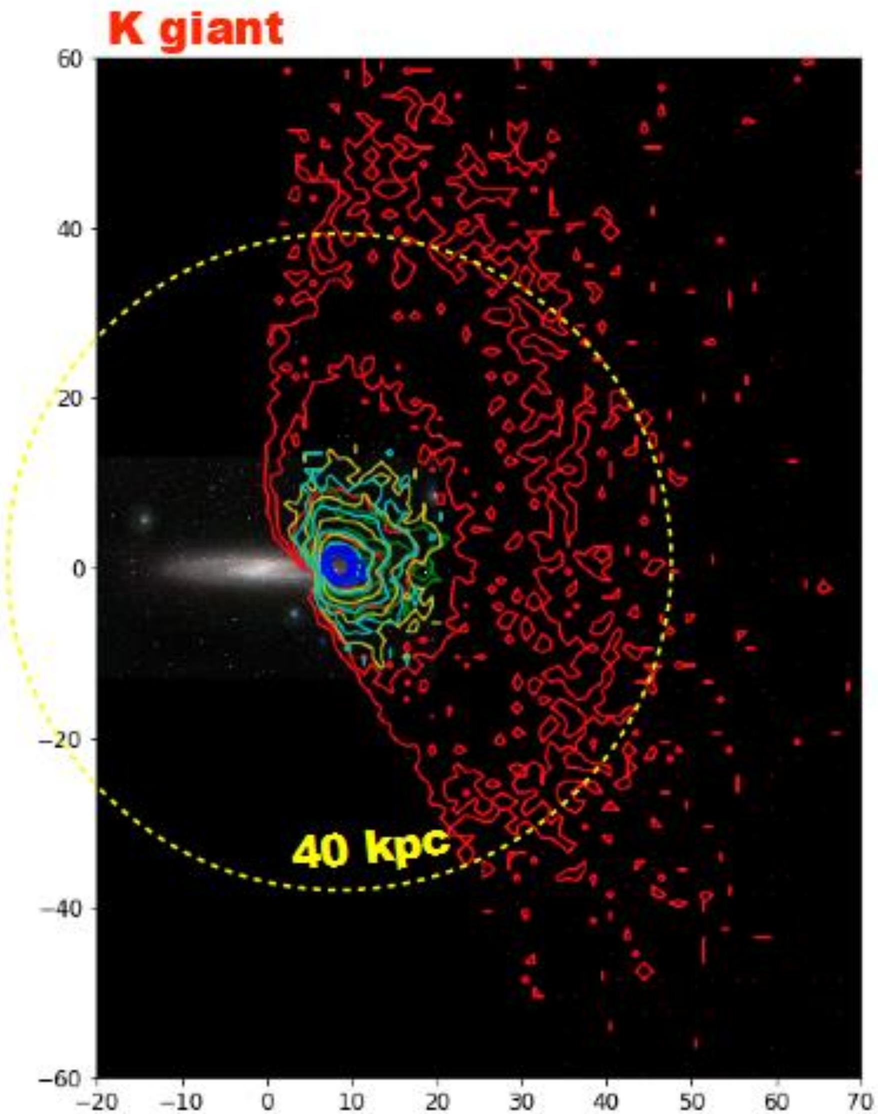


Zhao et al. 2015, RAA, 15, 1378



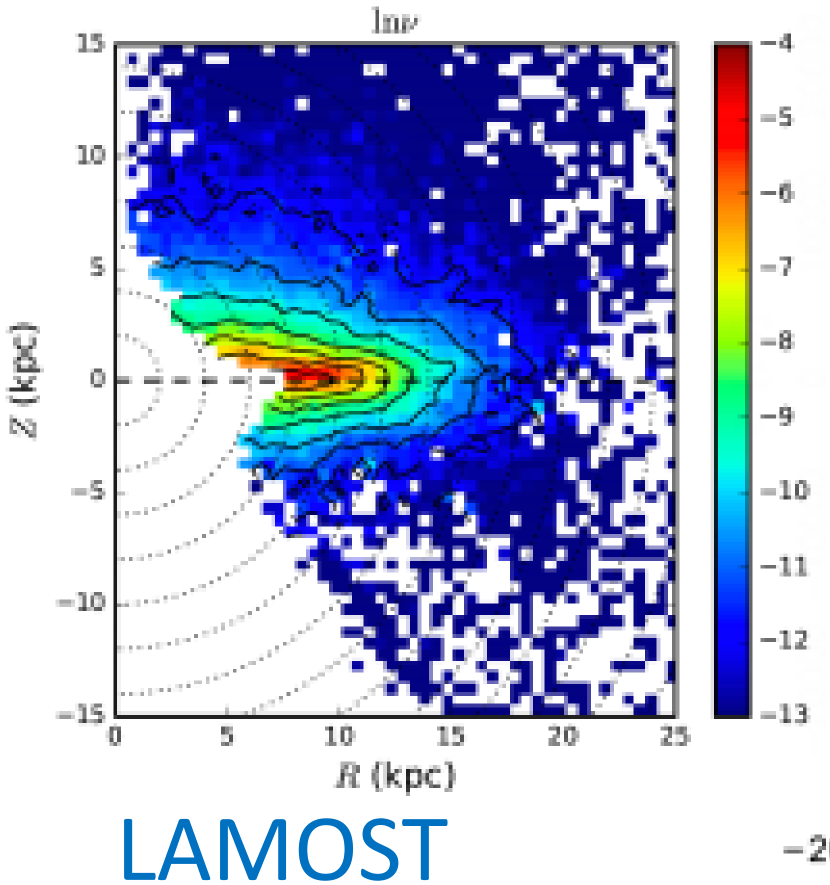
- LAMOST DR1: 7,993 FGK dwarfs (< 2 kpc), 3 new moving groups (two in the thick disk, one in the halo) found.
- LAMOST DR2: (< 2 kpc) 64,819 FGK dwarfs (< 2 kpc), and ([Fe/H] < -0.7 dex), 6 new moving groups found.

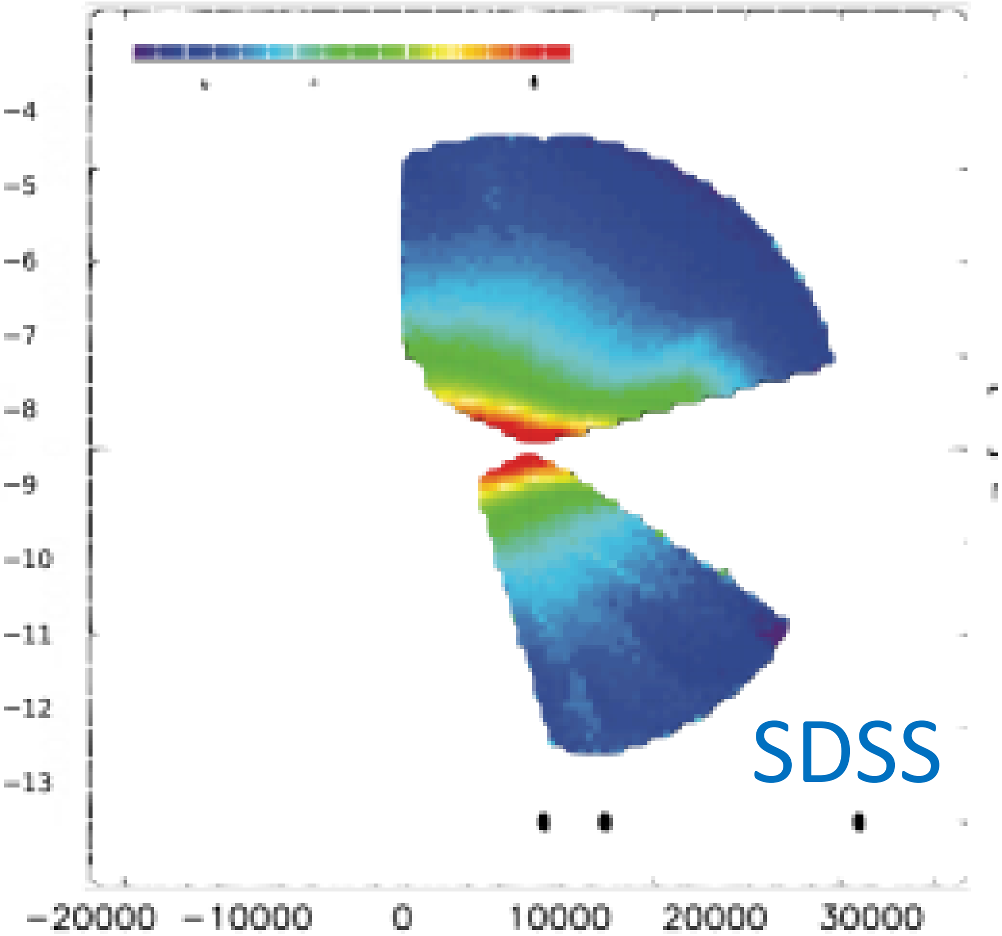
Structure and evolution of the Galaxy


K giant
60
40
20
0
−20
−40
−60
−20
−10
0
10
20
30
40
50
60
70
40 kpc

Shape of the outer disk

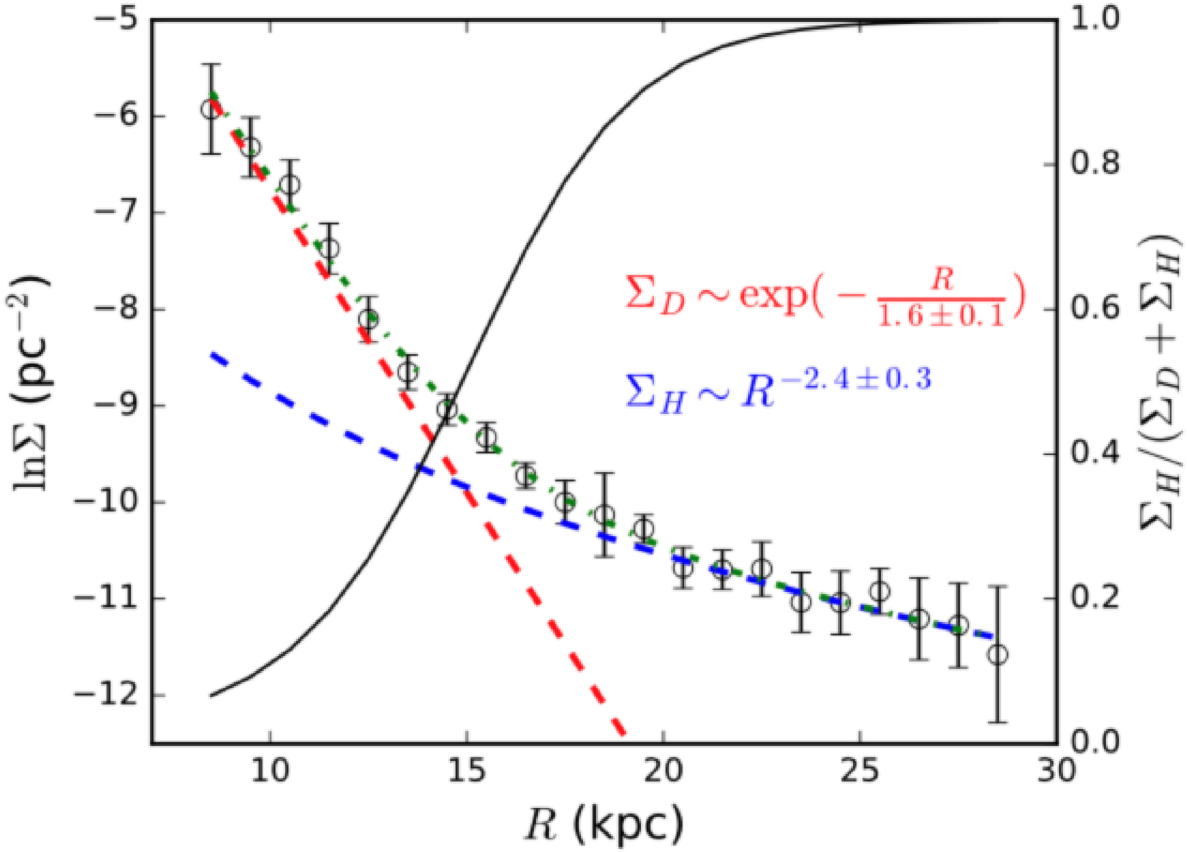
Juric et al. 2008





~22000 RGB stars from DR3 with MK<-3.5mag

The radial profile

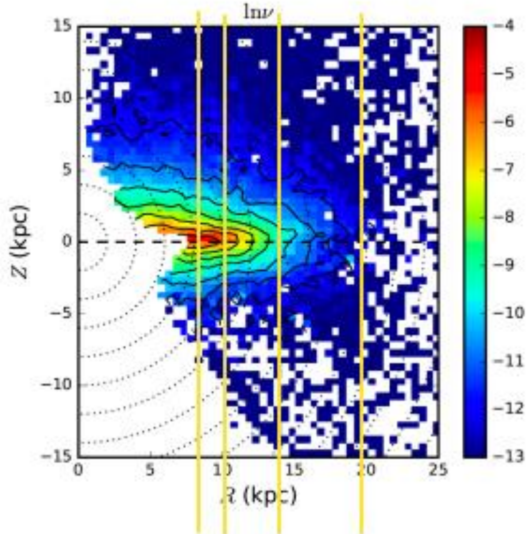


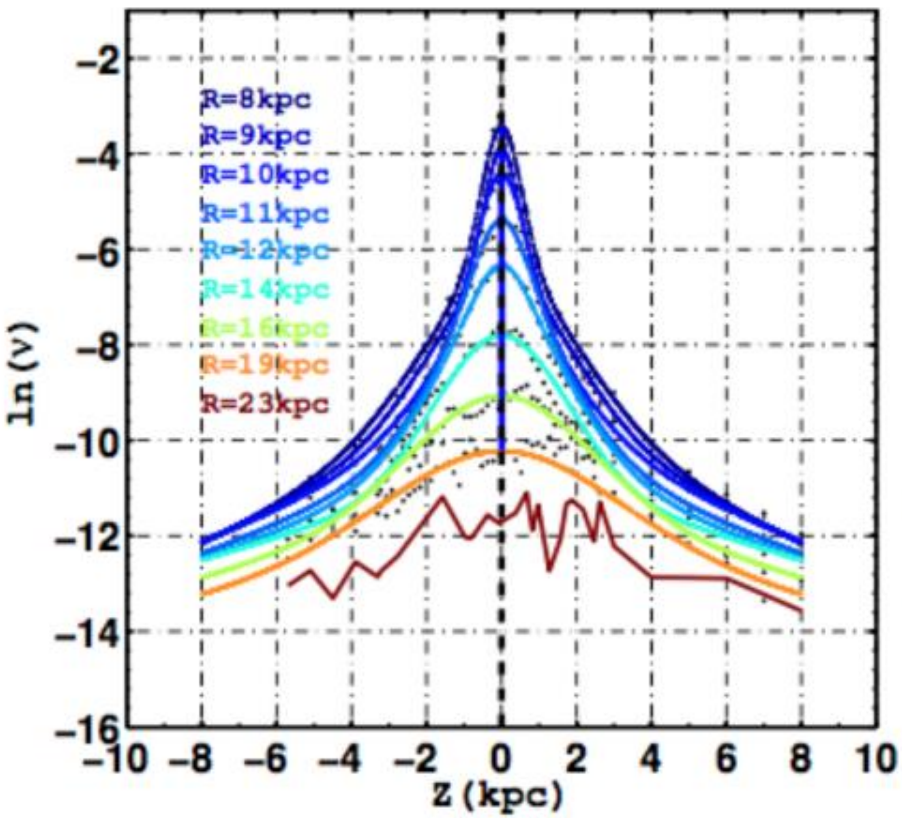
- The disc is more extended
- At R=19kpc, the fraction of disc pop. is still ~10%
- No truncation, break, bend-up feature is found in the outer disc
- It simply follow an exp. profile and smoothly transition to the halo

Liu et al. 2017 RAA, arXiv:1701.07831

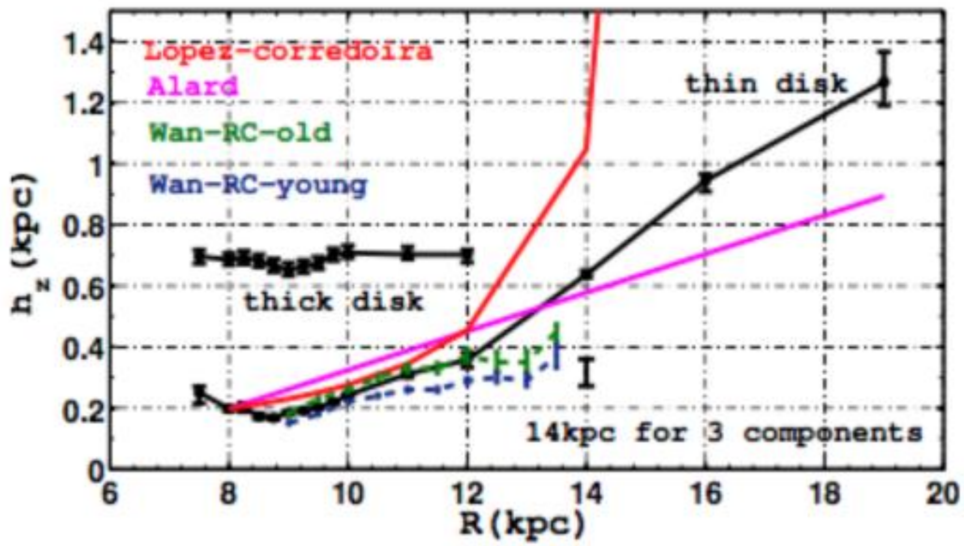
Wang, Liu et al. to be submitted

Flaring

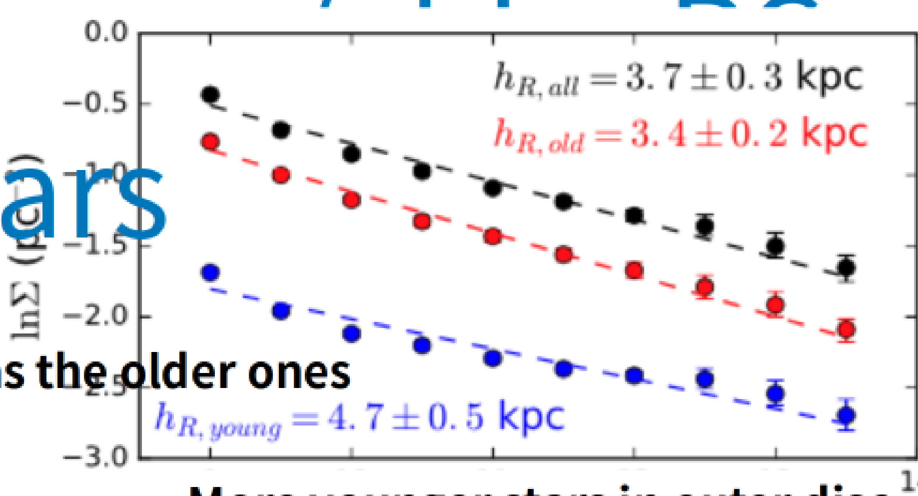




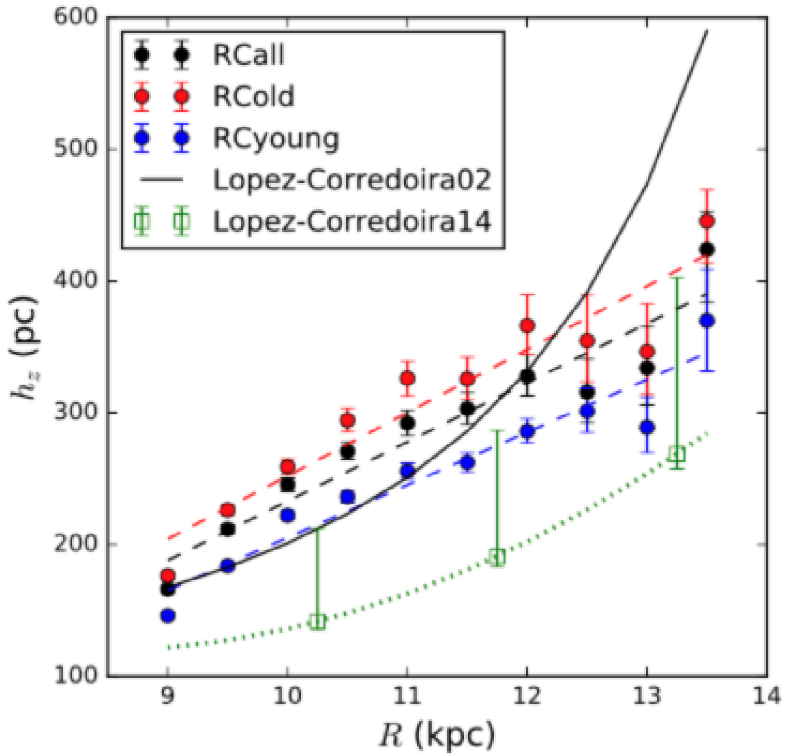
Thick disc hz is subject to around 0.7kpc as a prior



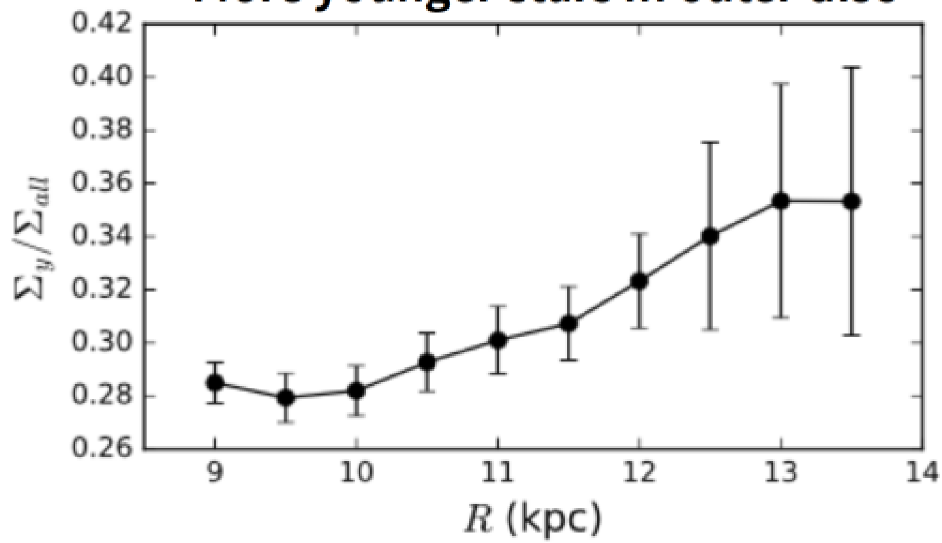
Flaring in yo
stars



Younger populations also show flares, as the older ones



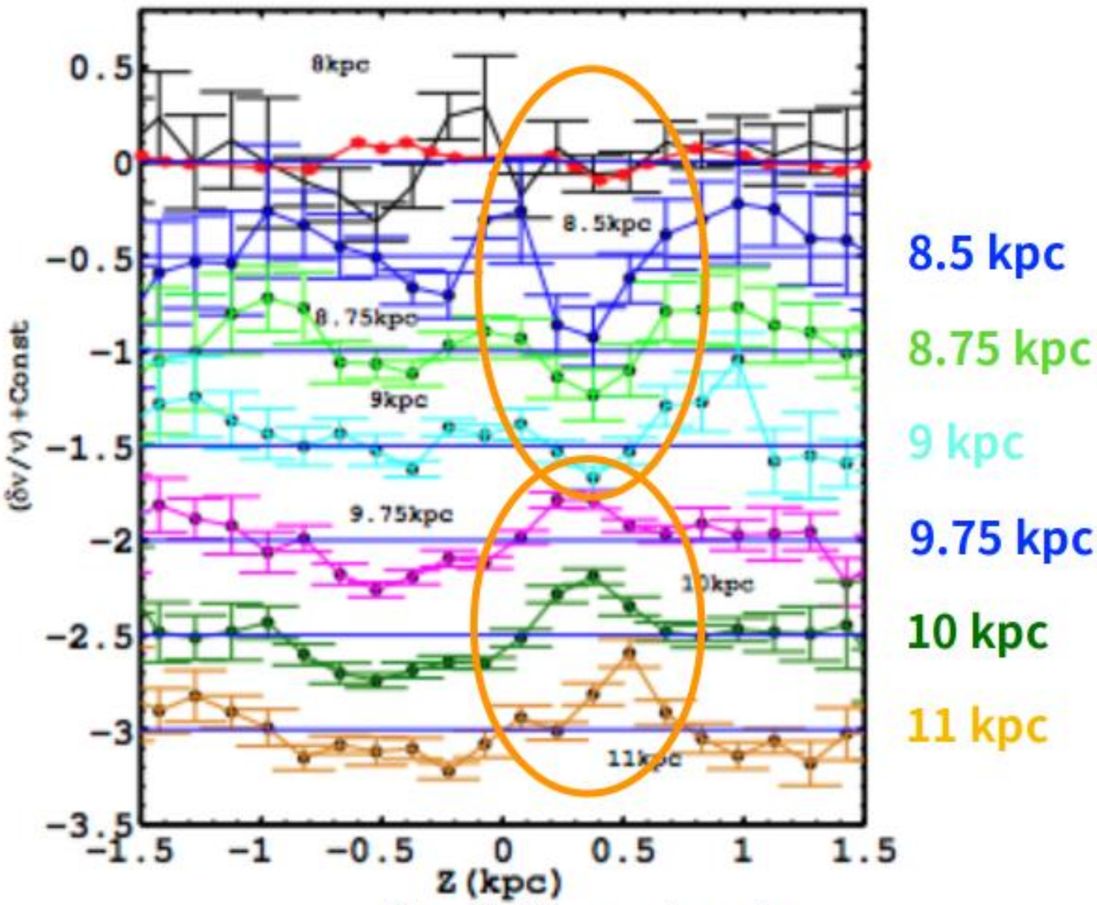
More younger stars in outer disc



Younger(~2Gyr)/Older(~4Gr) red clump stars

Wan, Liu et al. 2017, RAA in press, arXiv:1704.04369

Wobbly disc



North Near structure

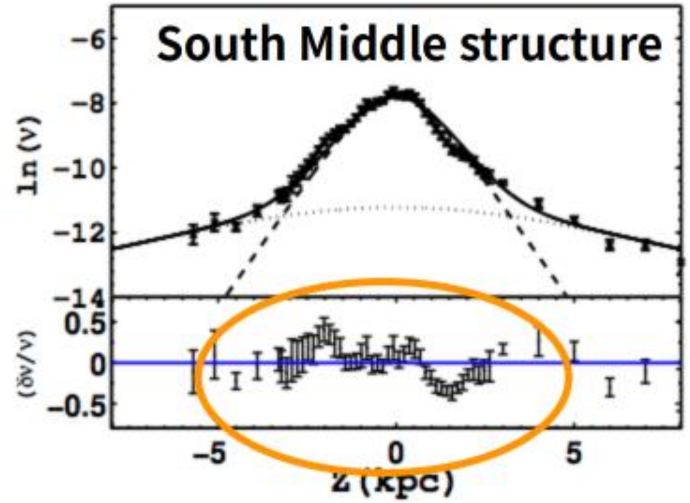


Fig. 37.— Similar with the Figure 15, but for 14 kpc.

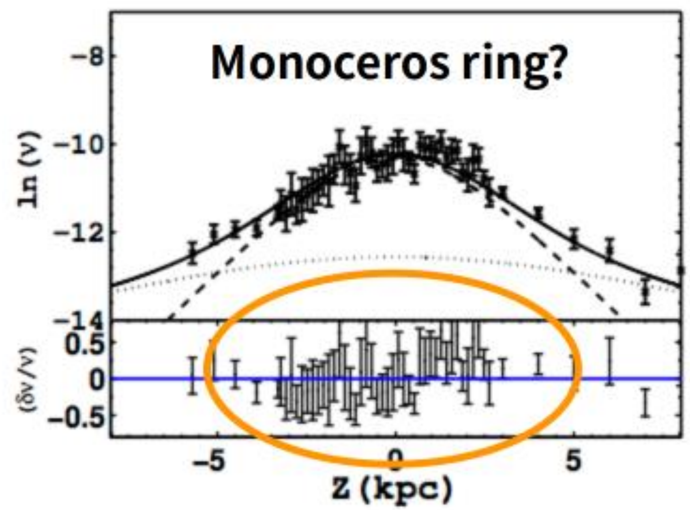
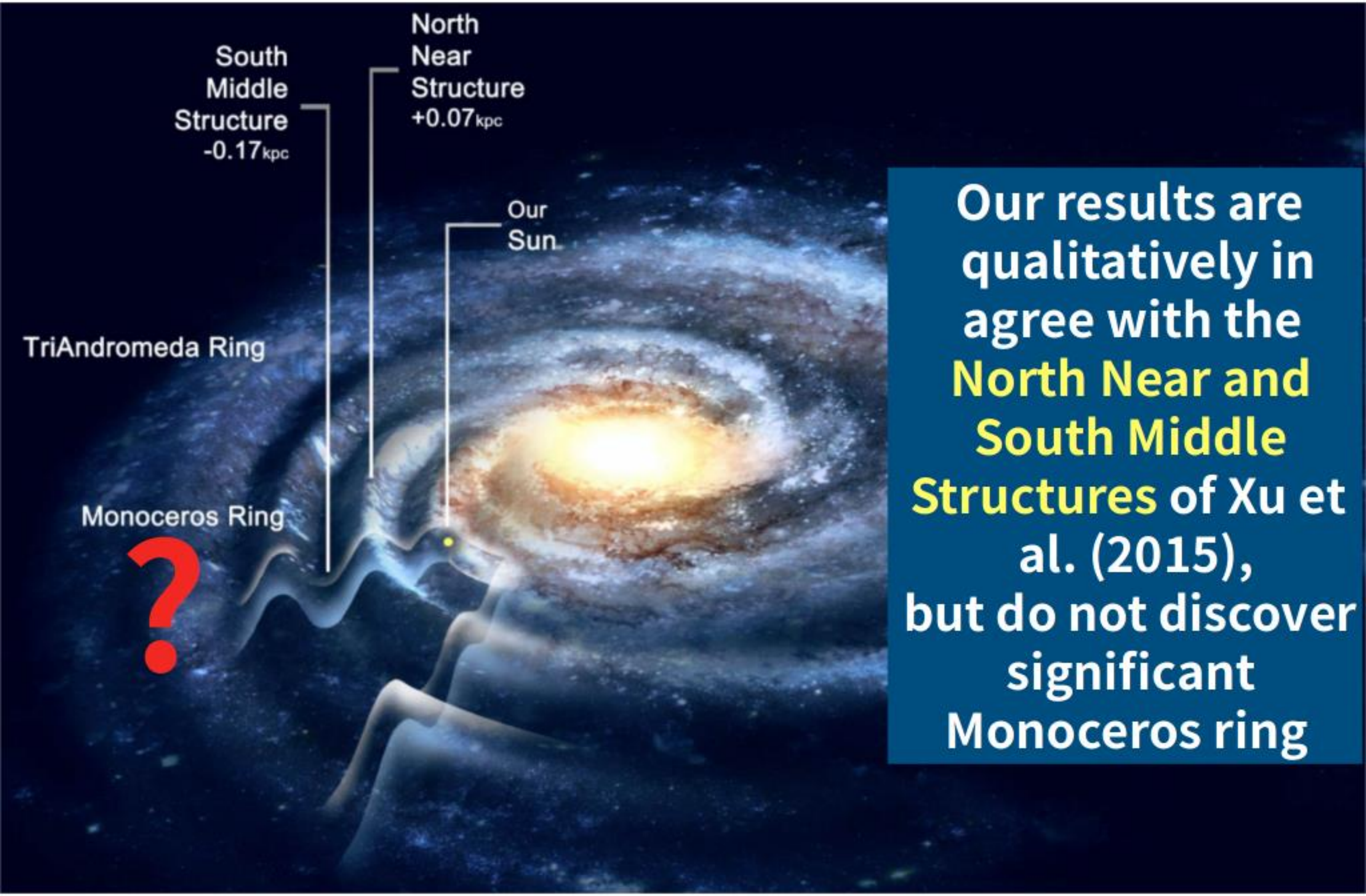


Fig. 41.— Similar with the Figure 15, but for 19 kpc.

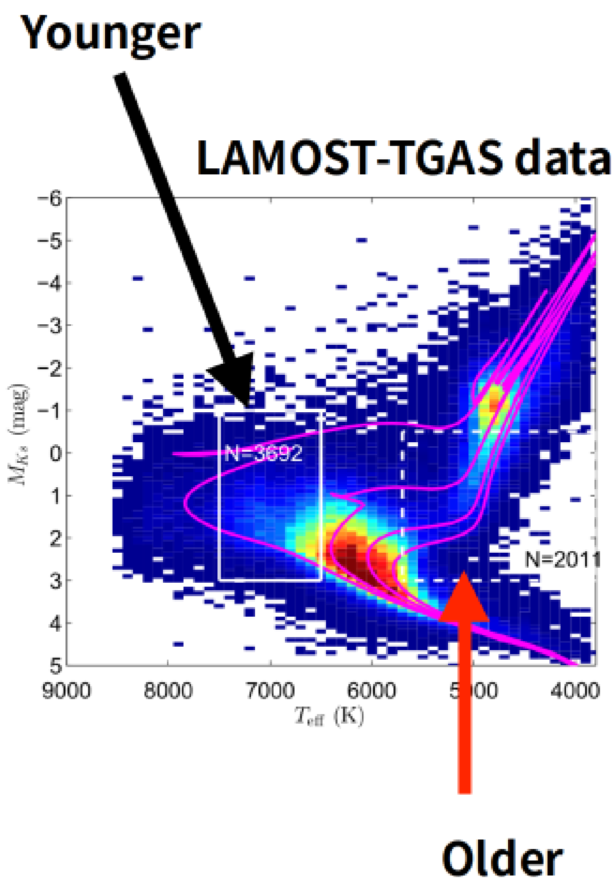
Wang, Liu et al. to be submitted

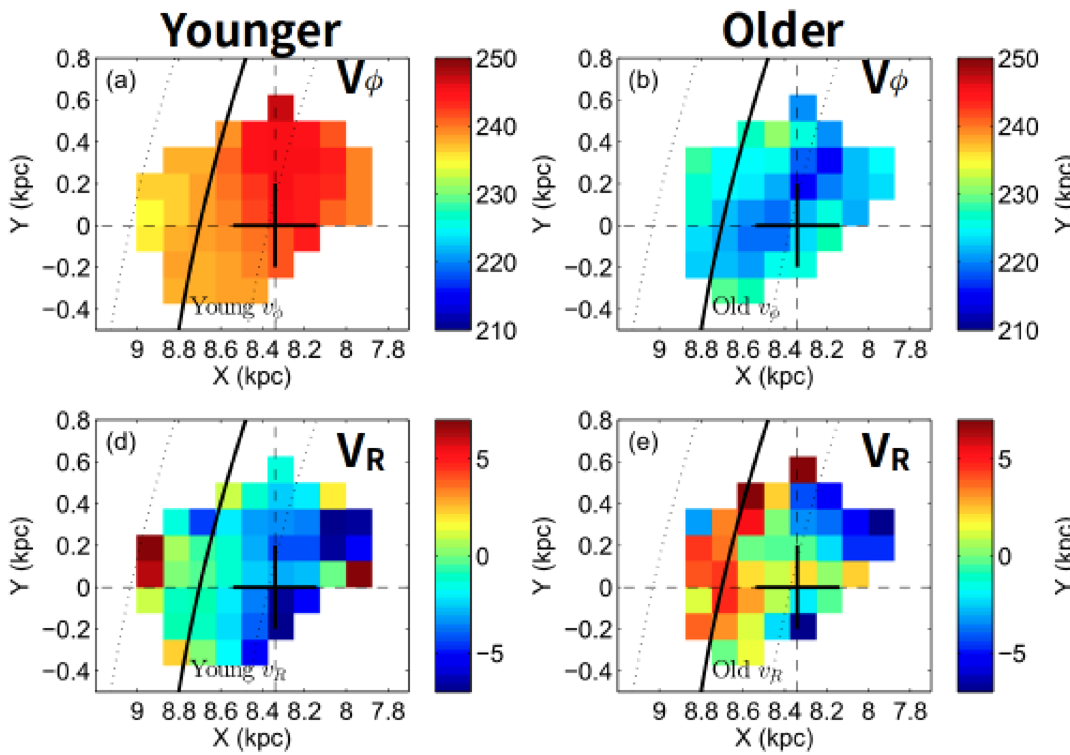


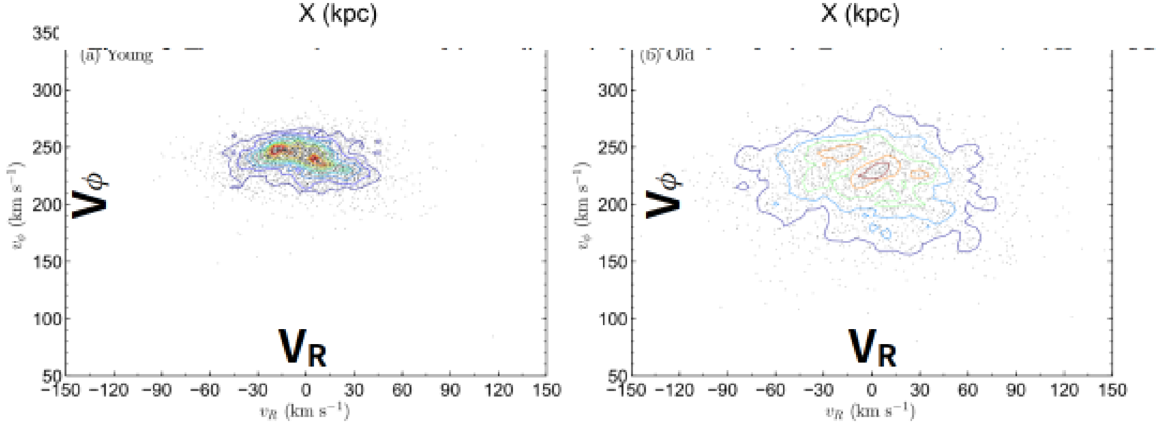
Our results are qualitatively in agree with the North Near and South Middle Structures of Xu et al. (2015), but do not discover significant Monoceros ring

Liu et al. 2017 ApJ, 835, L18

Velocity field in SN

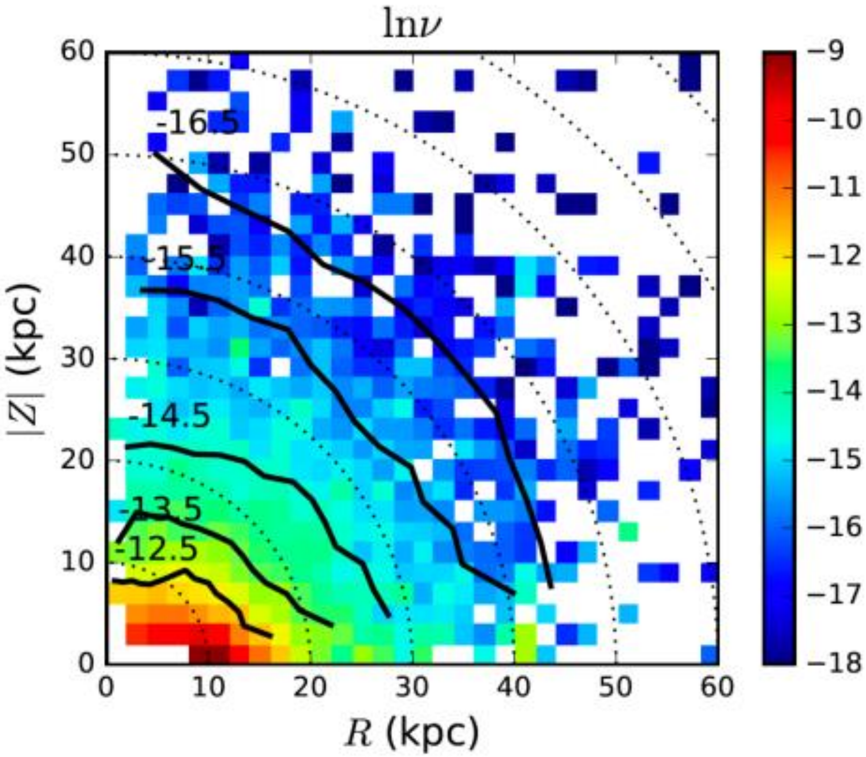




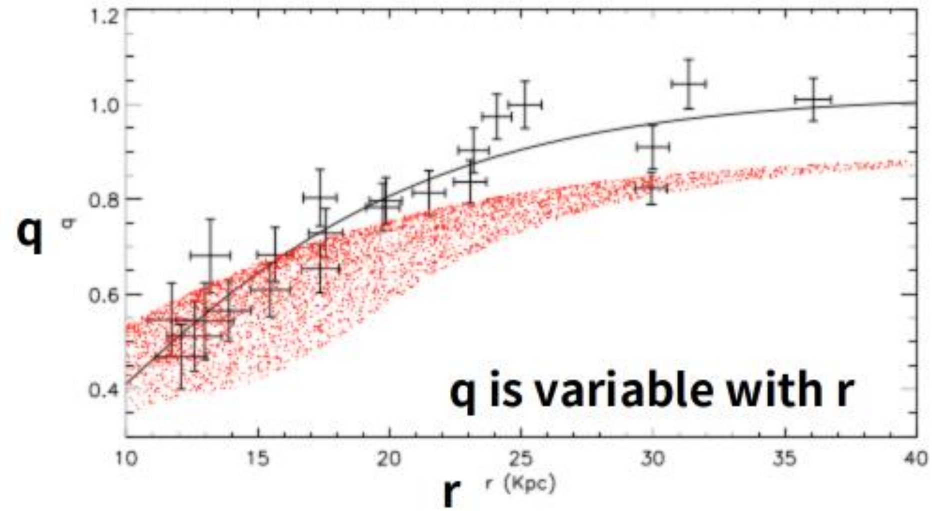


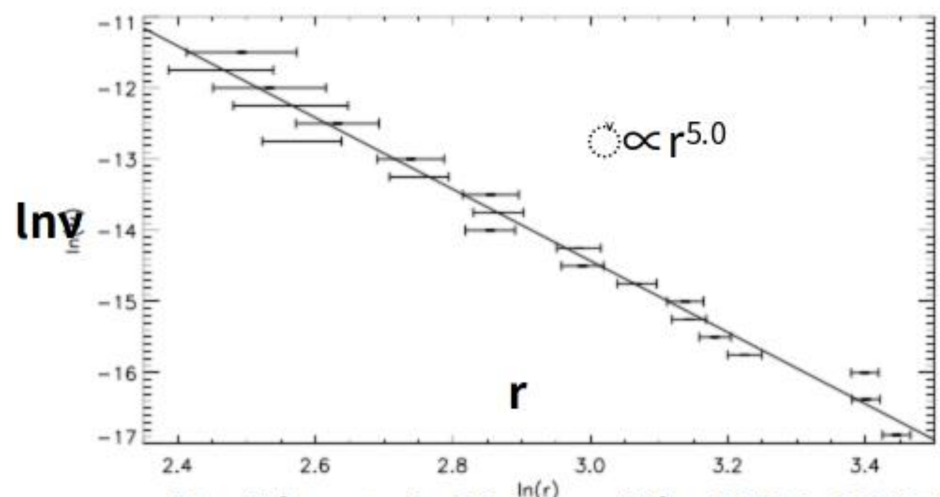
The halo—density profile

5000+ **RGB** stars from DR3 with [Fe/H]<-1dex and MK<-4



Liu et al. 2017 RAA, arXiv:1701.07831





Xu, Liu et al. 2017, arXiv:1706.08650

Mass profile from K-giants

Results for LAMOST + SEGUE halo K-giant stars with Galactocentric radius of 16 – 85 kpc:

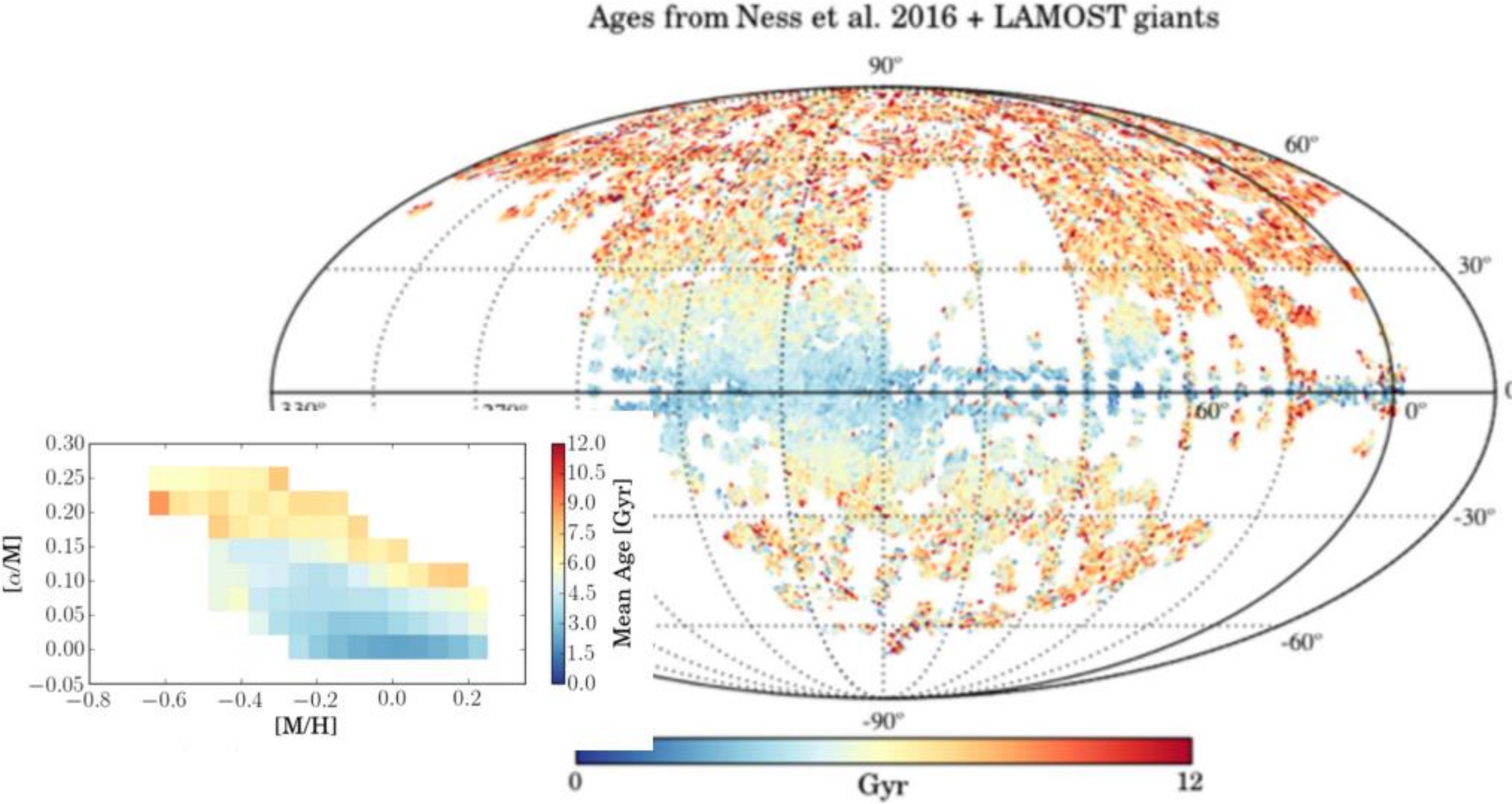
- total number of tracers $N = 5734$ K giants
- Milky Way mass out to 85 kpc: $0.7 \pm 0.1 \times 10^{12} \mathrm{M}_{\odot}$

Extrapolate mass out to the virial radius r_{vir}

- Subtract bulge and disk mass: $5.9 \times 10^{10} \mathrm{M}_{\odot}$ Binney & Tremaine 08, Bovy & Rix 13
- Fit the mass profile from LAMOST with Navarro-Frenk-White dark halo density profile
- Best fit parameters: $r_{\mathrm{vir}} = 208$ kpc and concentration $c = 26$
- $\Rightarrow$ result: $M(r_{\mathrm{vir}}) = 0.9^{+0.6}_{-0.3} \times 10^{12} \mathrm{M}_{\odot}$
- Comparable mass to Huang+16

Ho et al. 2017 ApJ

K giant stars: [C/N]->Mass->Age

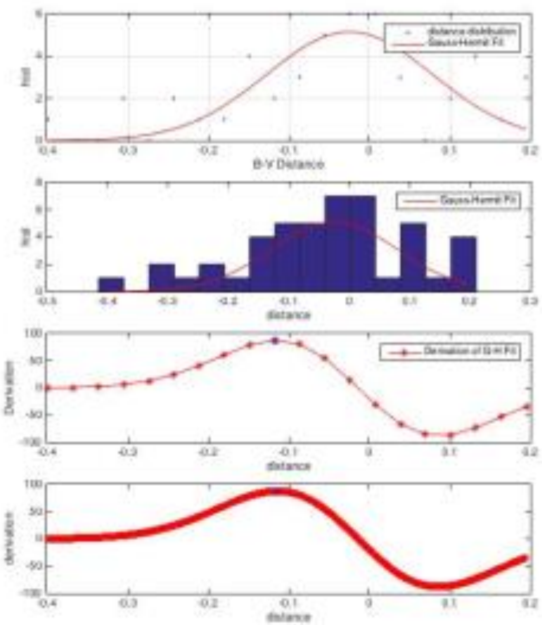


Ages will play important role in future works

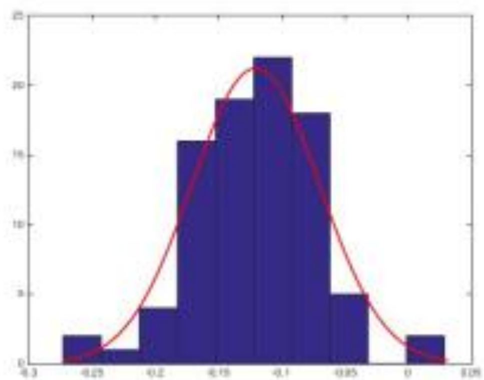
Age of halo

Guo et al. in prep.

The halo age property as revealed by LAMOST-GAIA data



After 100 simulations--->11Gyr



Sigma=0.0504--->3.3 Gyr

11.0$\pm$ 3.3 Gyr (average B-V error = 0.066)

10.5$\pm$ 1.5 Gyr (average B-V error = 0.02)

Next step:

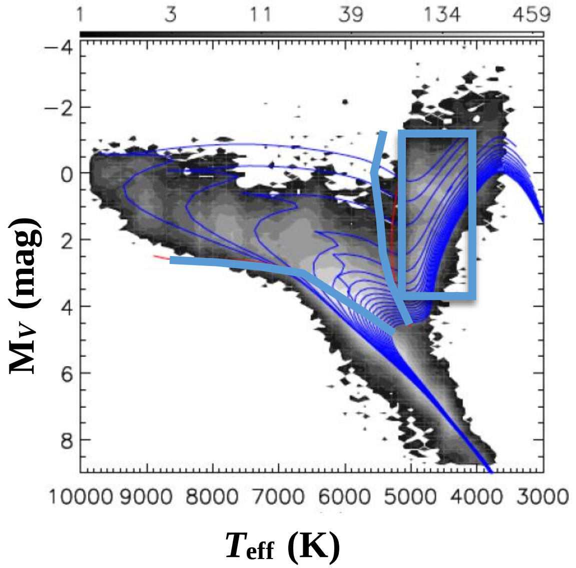
- Determine ages of all halo stars
- Combine orbital information,
- Get rid of thick disk
- separate inner halo, outer halo.

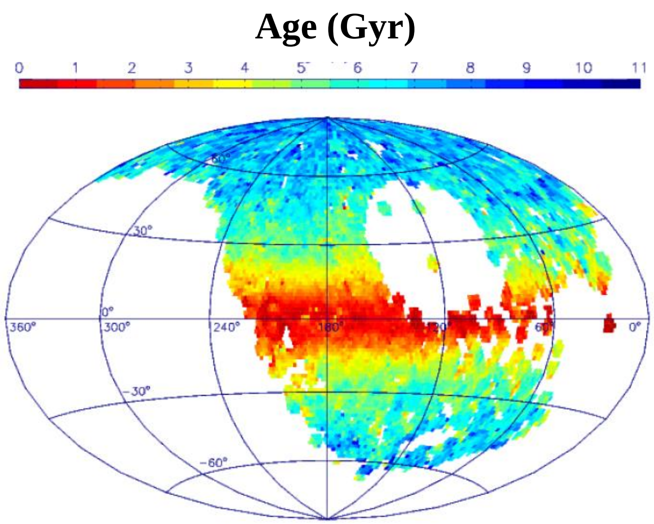
Only LAMOST?

-5<[Fe/H]<-1.0, Teff<8000, |vr|<500, SNR_B>15---->116820

200<=sqrt((v+220)^2+u^2+w^2) <=500 -----> 49412 left

Revealing the Galactic assemblage history





Stellar ages for millions of MSTO and RG stars, with uncertainties of 20-30%

Mapping the chemistry, kinematics/dynamics, matter distribution, spatial structure, star formation rate of mono-age stellar population

LAMOST + Gaia (DR2+) will be the golden source for Galactic archaeology in the next few years

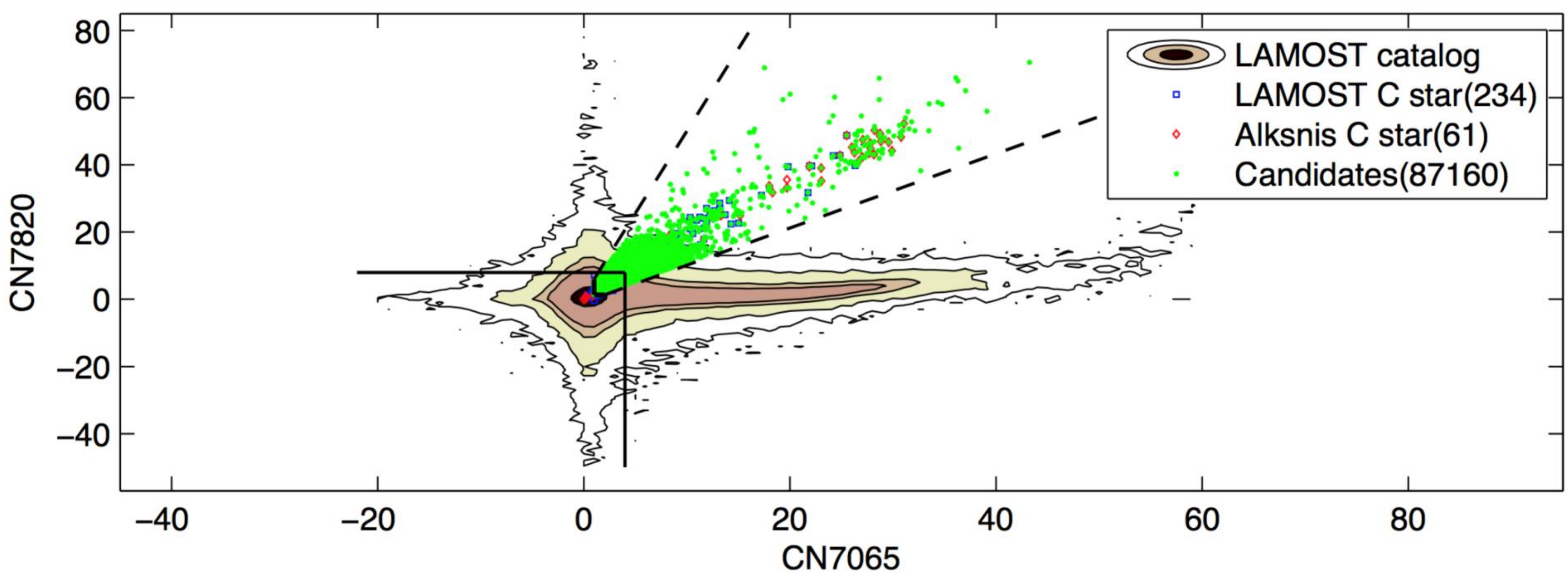
Ages of 1 million MSTO stars
(Xiang et al., ApJS, submitted)

Referee: This is a solid body of work that makes a significant contribution to the field, and which is especially valuable as a benchmark for galactic evolution modeling.

Stellar physics

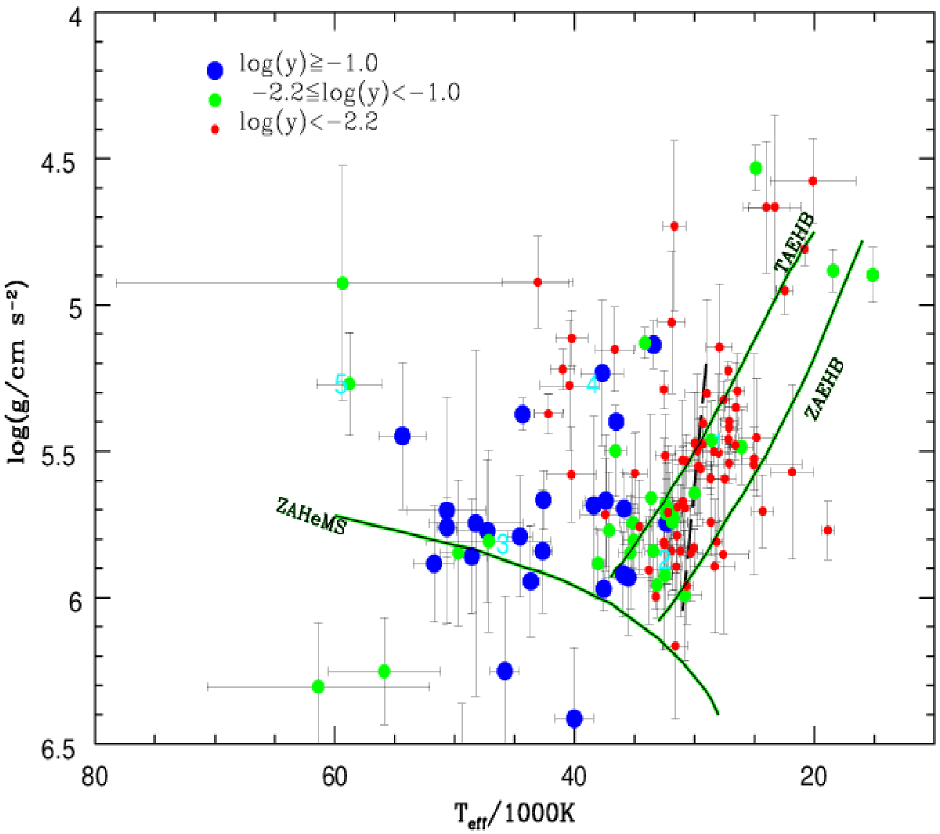
Carbon stars from LAMOST DR2 data

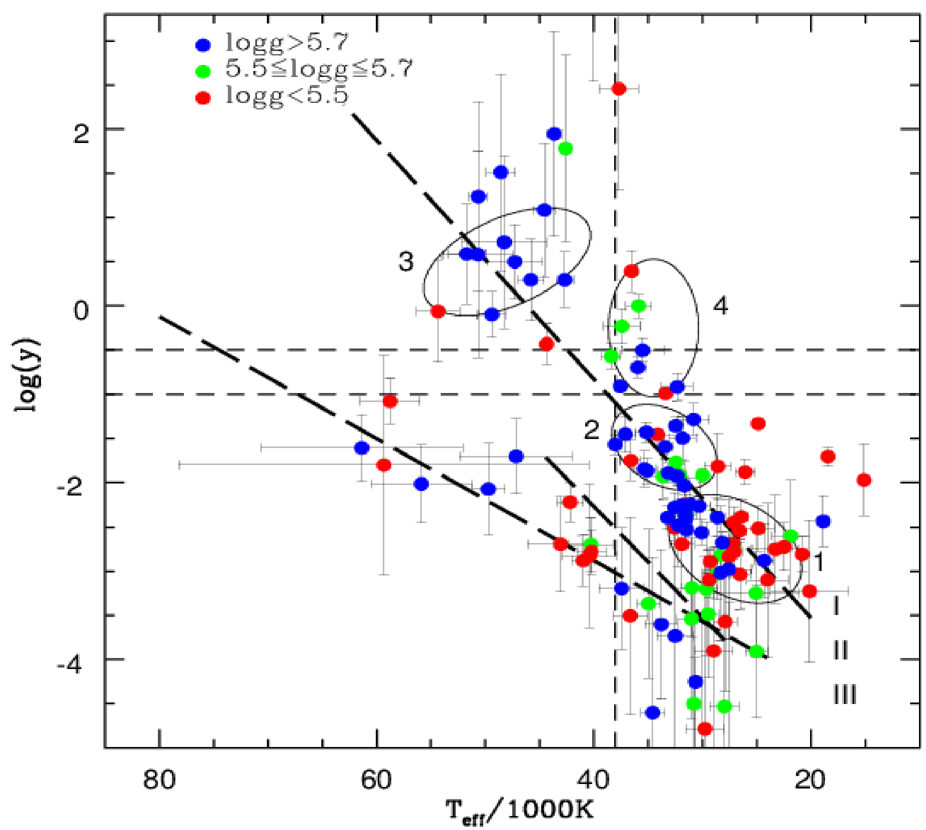
- identify 894 carbon stars from the LAMOST DR2 database
- spectral line indices of CN at around 7820Å and 7065 Å



Hot Subdwarf Stars Observed in LAMOST DR1

- a catalog of 166 spectroscopically identified hot subdwarf stars from LAMOST DR1

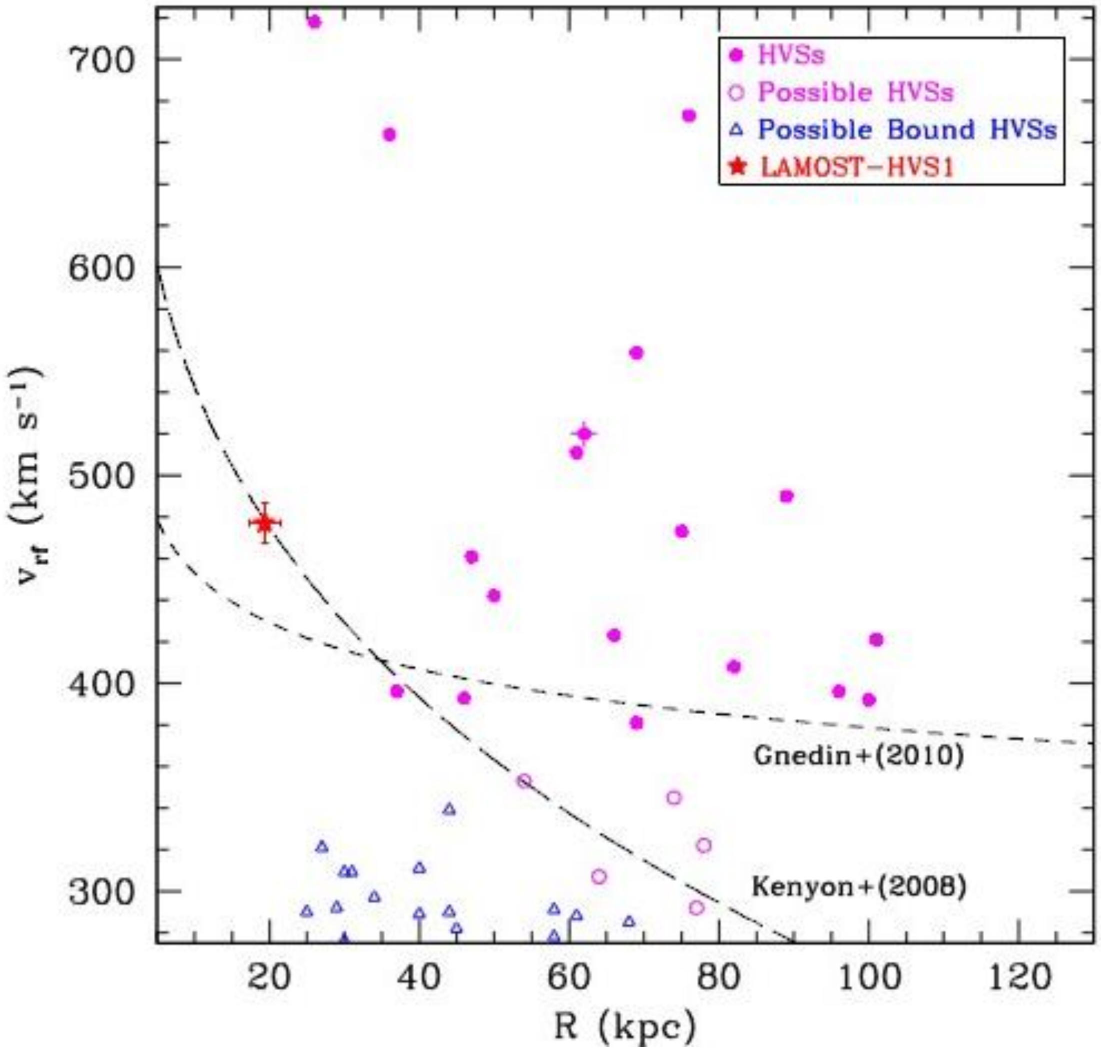




Hyper-velocity stars

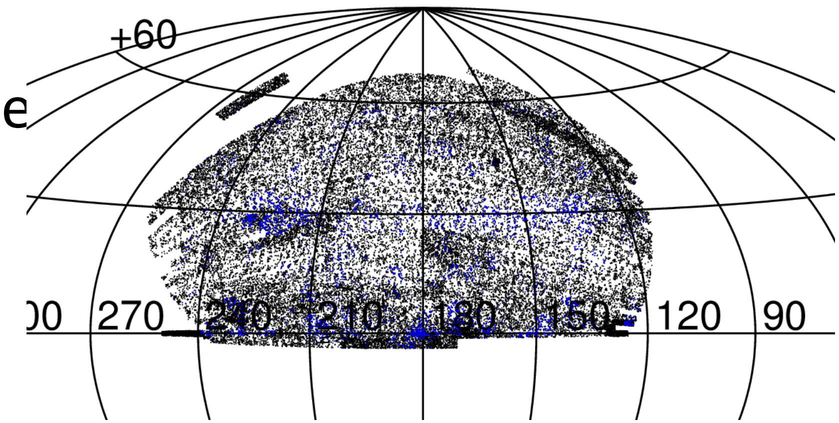
Zheng et al. 2014

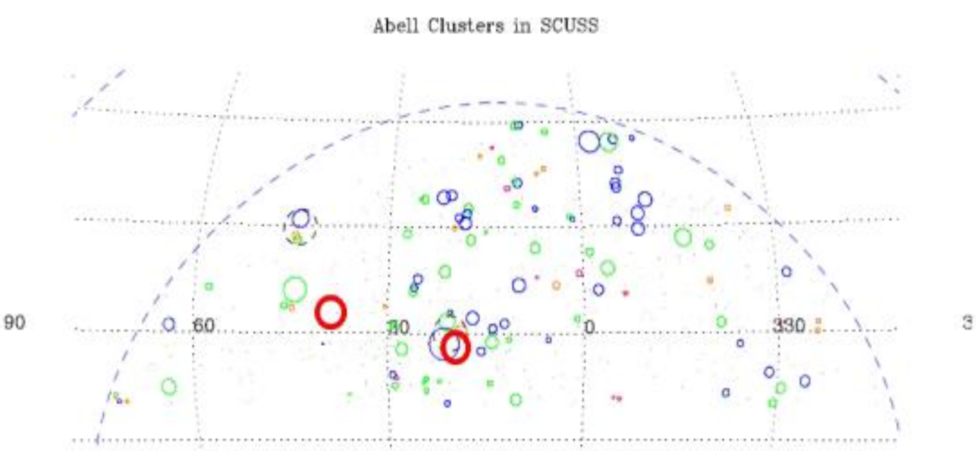
1. Central BH in the Milky way
2. Ia type supernova
3. dwarf galaxies

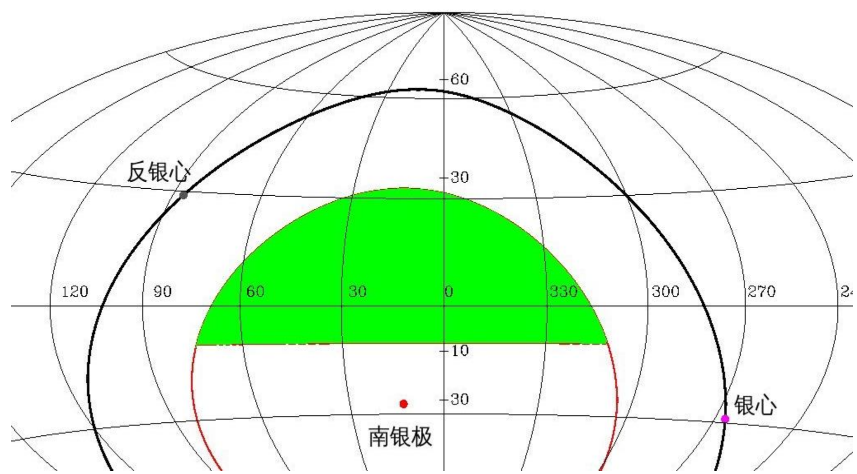


LAMOST Extra-GAlactic Survey (LEGAS) : initial plan

- North Galactic Cap
  - Complementary galaxy sample
- South Galactic Cap
  - Main galaxy sample
  - Emission line galaxy
- Two complete fields





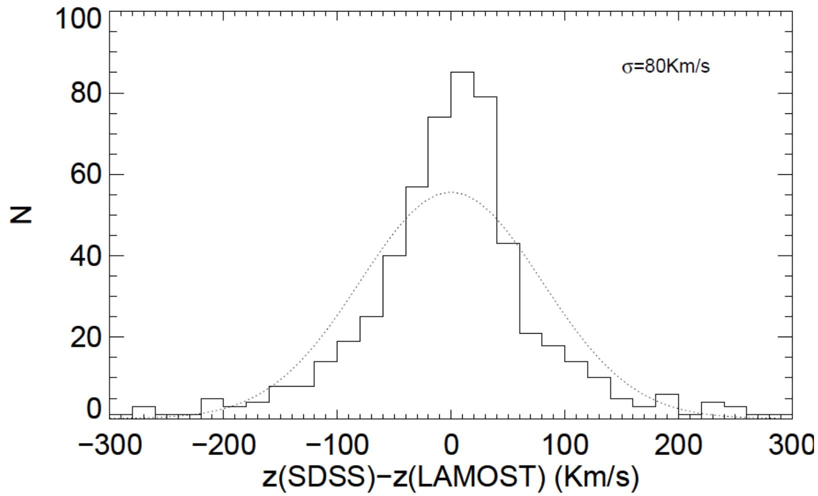


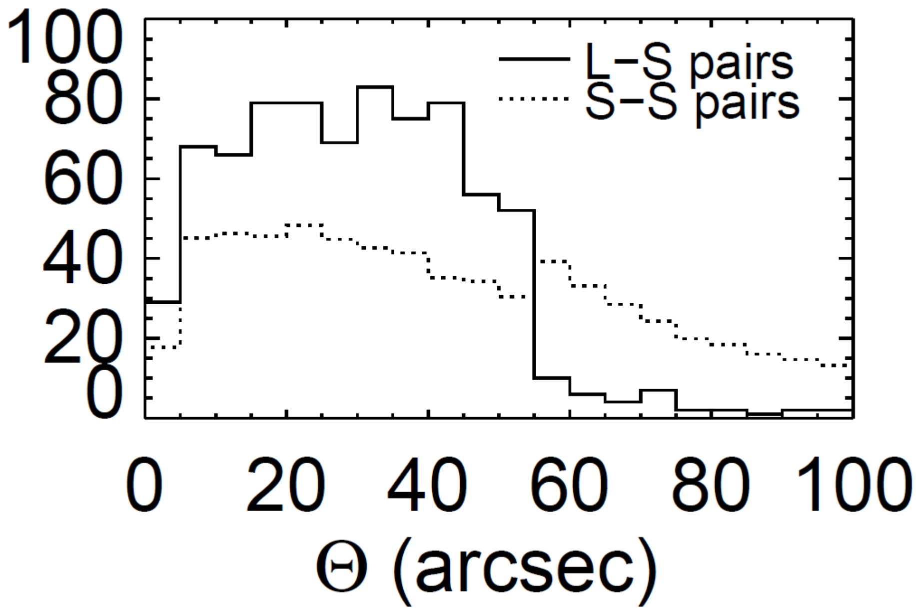
New L-S galaxy pair sample

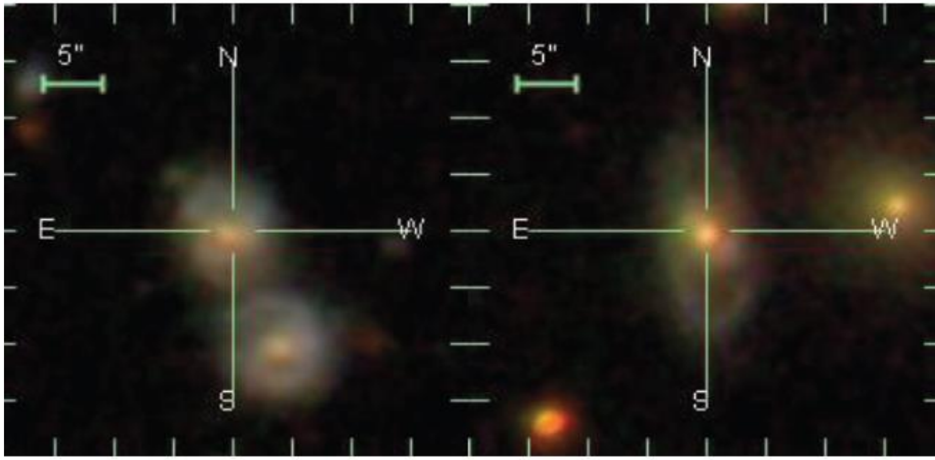
Shen et al., 2015

1807 complementary galaxy with z

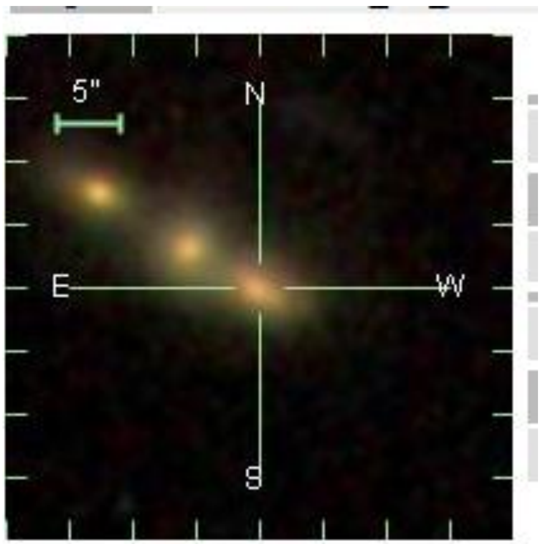
- 784 L-S galaxy pairs
  - P<100Kpc dV<500Km/s





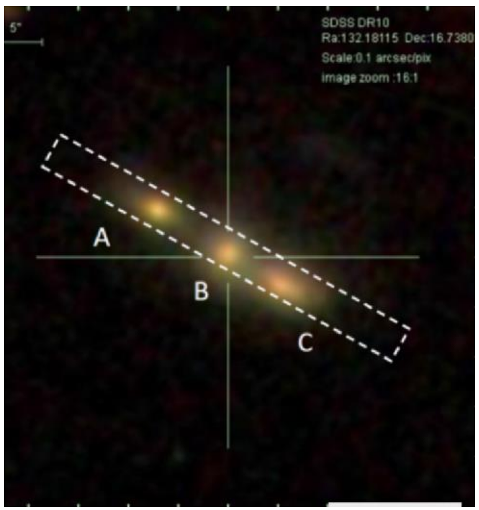


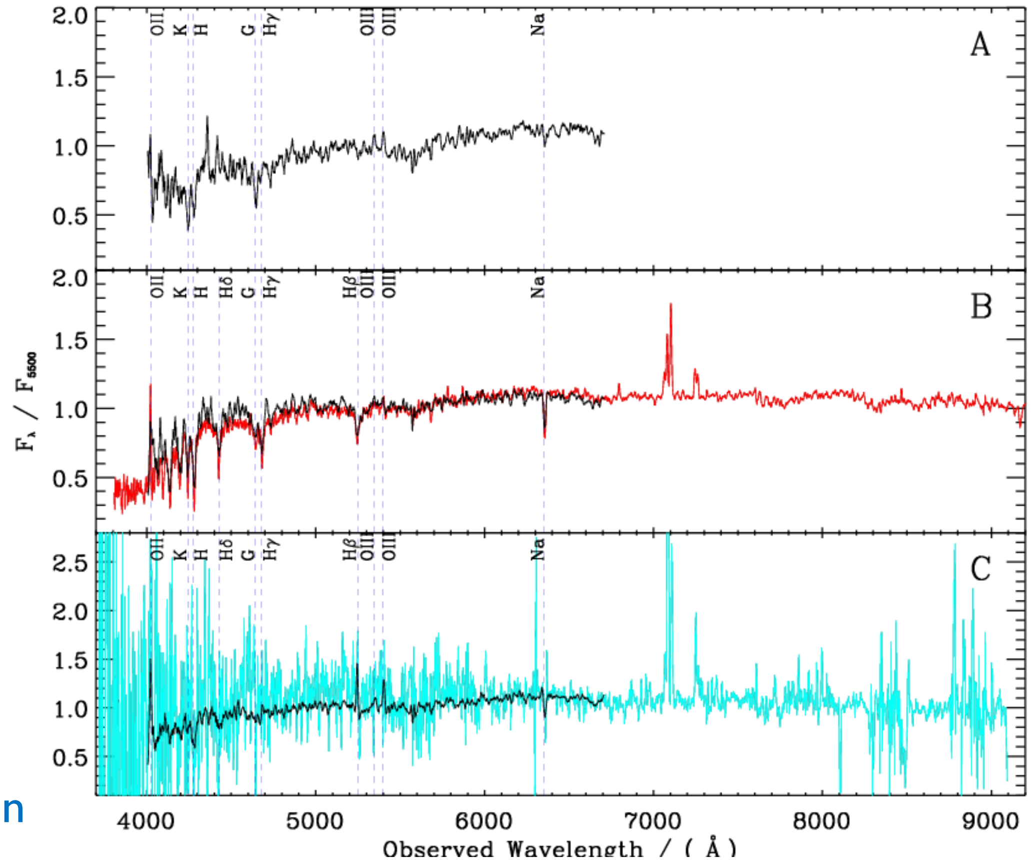
Multi system



302 of 784 pairs are actually in multi system

Discovery of an isolated galaxy triplet
(Feng et al. 2016)





Chain-like structure

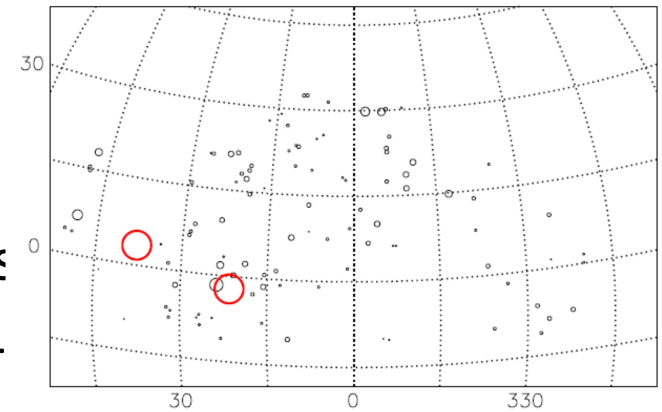
Formed in early time

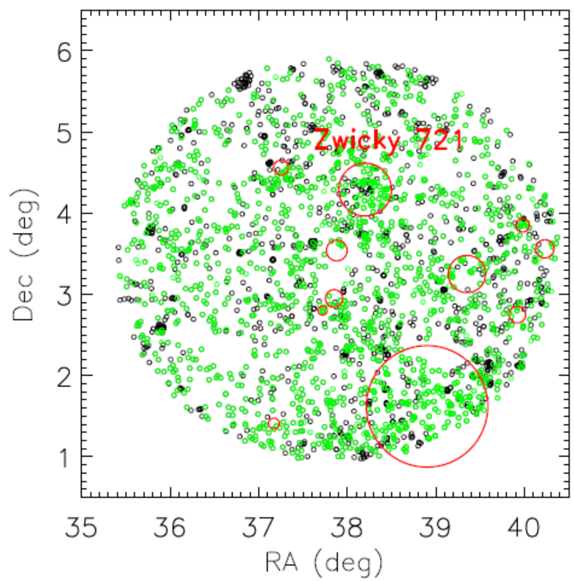
Early type galaxies with Halpha emission

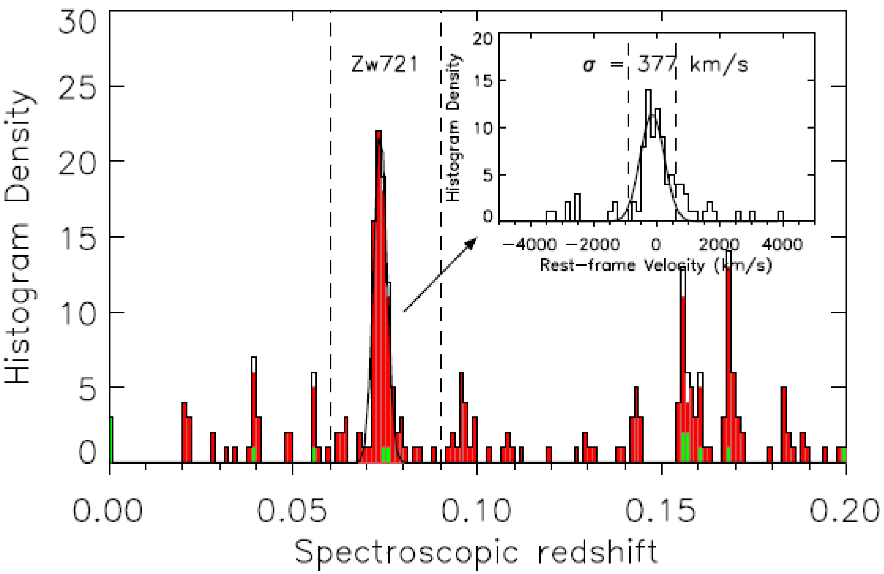
recent star formation

Two complete fields

- Ra = 37.8, Dec = 3.4
- Ra = 21.5, Dec = −2.20
  - r<18.1 mag
  - ~5000 galaxies, 25000 point sources
  - 28 plates observed from 2012-2014



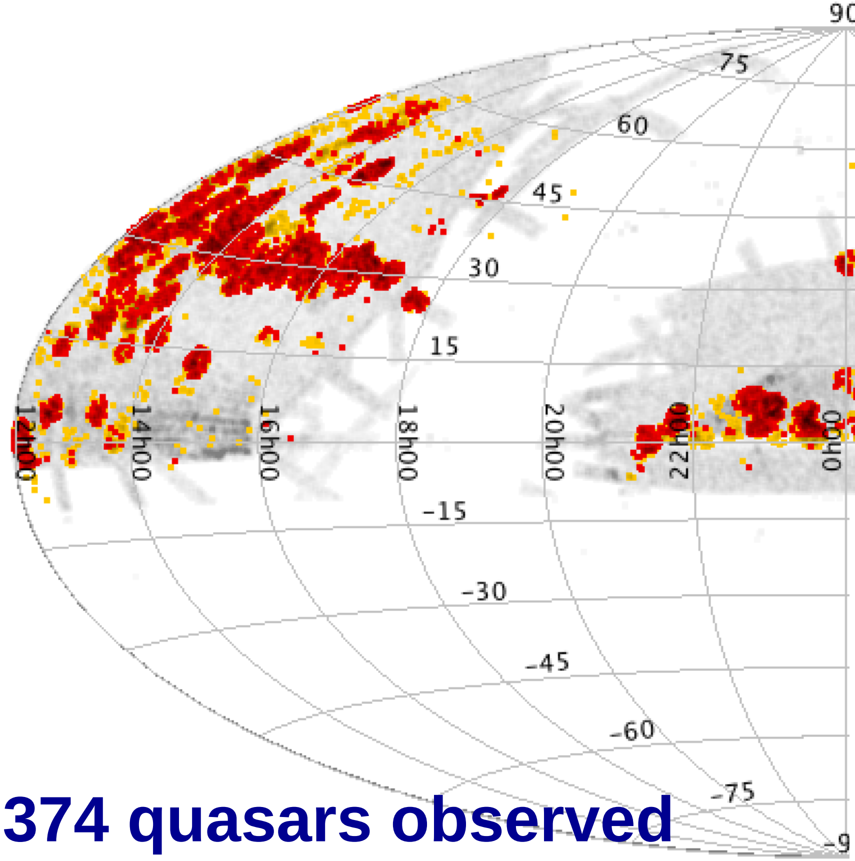


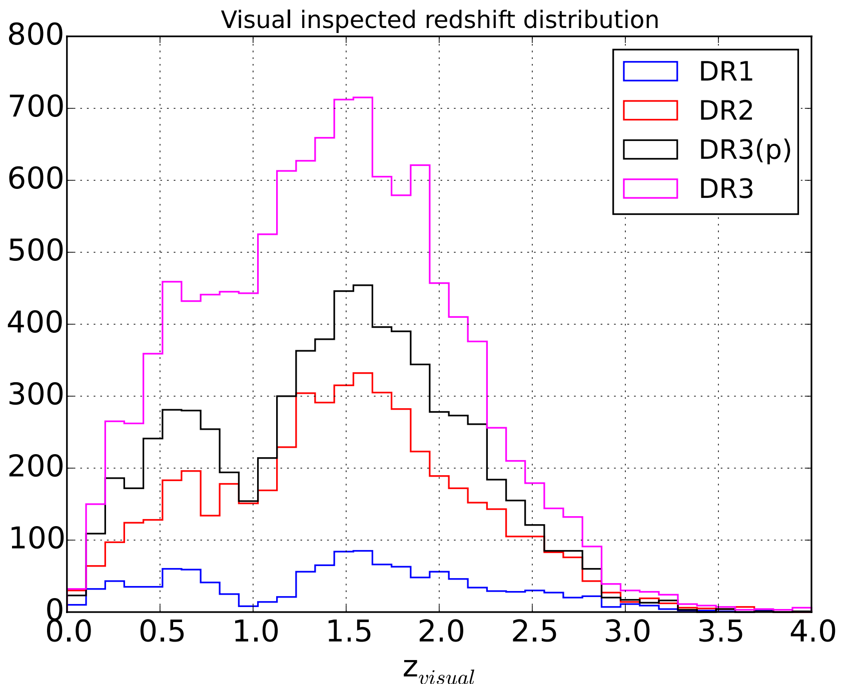


Special galaxies/multi-wavelength study

- 70 E+A galaxy sample (Yang et al. 2015)
- 20 double peaked narrow emission line galaxies and AGNs(Shi et al. 2014)
- 64 luminous infrared galaxies in two complete fields(Lam et al. 2015)
- Green Pea galaxy

LAMOST quasars：DR1-3





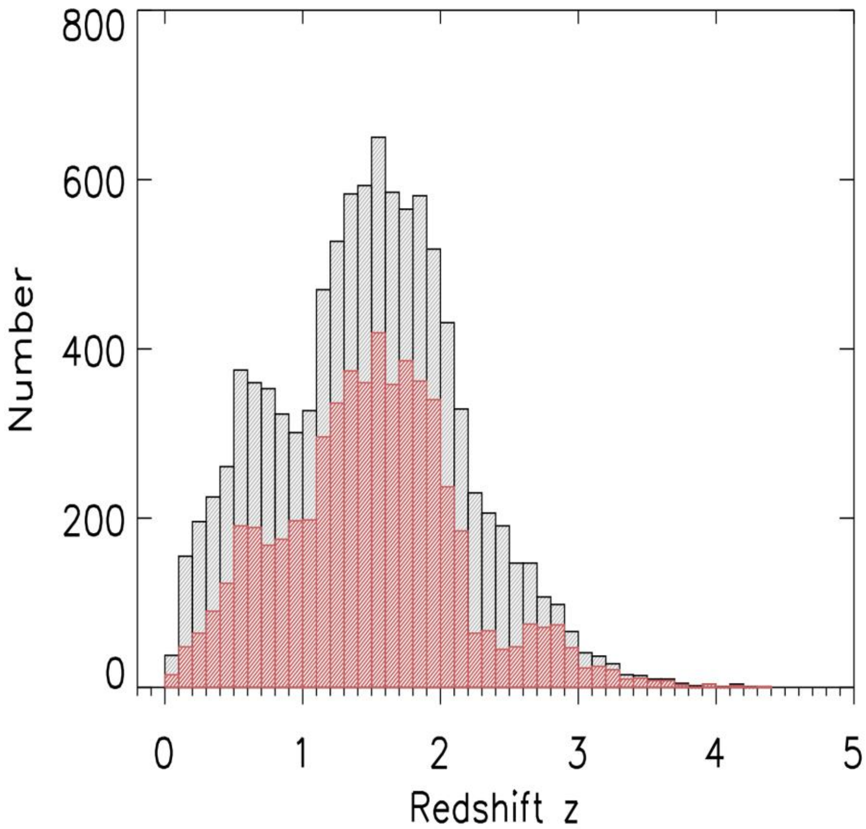
20374 quasars observed

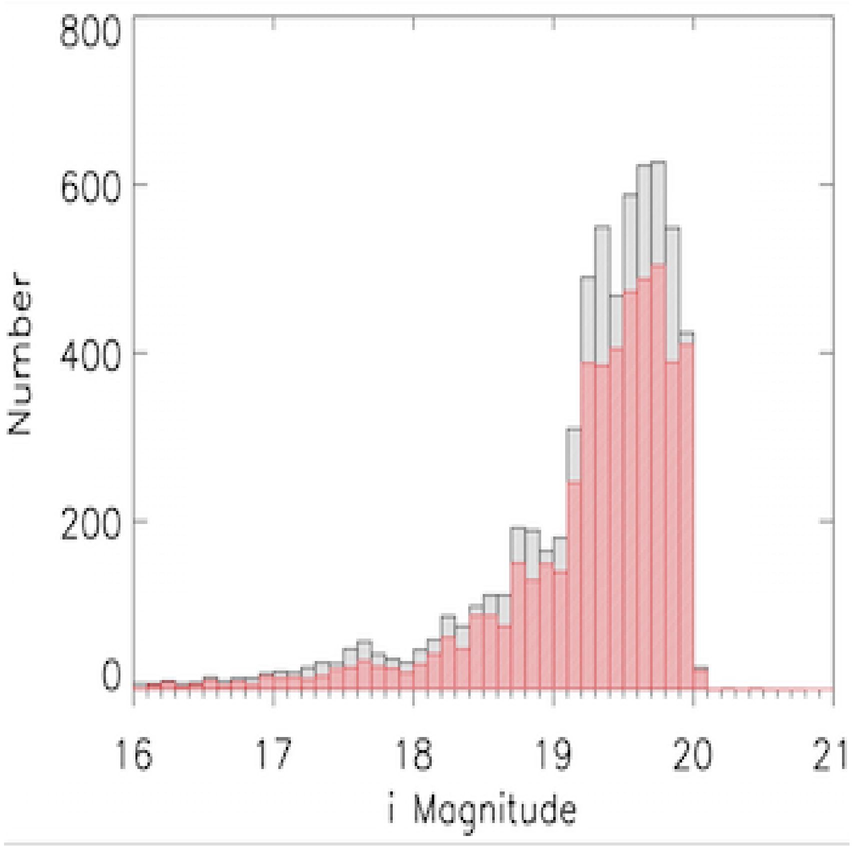
>8176 new quasars

(994 in M31/M33)

Dong et al. 2016 in prep.

Quasars in DR4 (on going)





New QSOs: 5718

Yao Su, et al., 2017, in prep

Summary

- By June 2017, the LAMOST Galactic surveys, initiated in October 2012, have obtained ~ 7.3M quality spectra. This number is still increasing at a rate of ~1M per annum;
- Two pipelines (LASP, LSP3) to derive basic stellar parameters (Vr, Teff, log g, [Fe/H]) have been developed, yielding parameters for ~2/3 of the spectra collected. It also yields pivotal abundance ratios ([α/Fe], [C/H], [N/H], etc.).
- This unique dataset has begun to yield an exquisite picture of unprecedented detail of the Galactic disk and halo, not only for the stellar populations (kinematics, chemistry) but also for the ISM (reddening, DIBs).
- To advance our understanding of the assemblage of the Milky Way and other galaxies and the origin of regularity and diversity of their properties.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2012.08.22 Nikon D90 + 10-24mm, F3.5, 14x30s, ISO2500
WWW.KARAJIN.COM

Thank You！

The Milky Way's escape velocity curve between 5 and 14 kpc

- Measurements of the Galactic escape velocities at Galactocentric radii between 5 and 14 are presented based on a sample of 527 high velocity halo stars ($|v_r| > 300$ km/s, [Fe/H] < -1) selected from the LAMOST Galactic spectroscopic surveys
- The local escape velocity is found to be between 500 and 558 km/s (90 per cent confidence level), with a median value of 529 km/s. The newly constructed Galactic escape velocity curve decreases steadily from 562 km/s at r ~5.9 kpc to 486 km/s at r ~13.2 kpc.

$$M_{vir} = (0.92 \pm 0.06) \times 10^{12}\ M_{\odot};\ \rho_{DM} = 0.33 \pm 0.02\ \text{GeV cm}^{-3}$$