Halo K-Giant Stars from LAMOST: Kinematics and Galactic Mass Estimate

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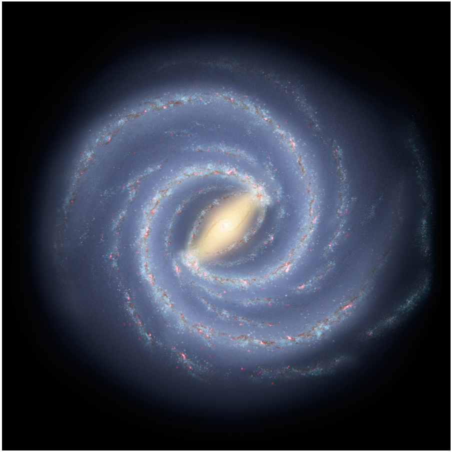
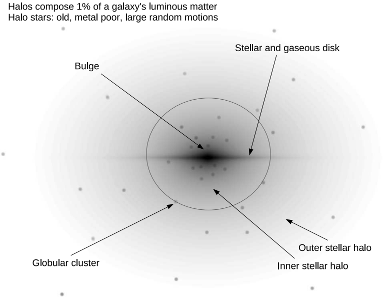
The Milky Way (Bland-Hawthorn & Gerhard 2016, Helmi 2008, Figure: NASA/JPL-Caltech/ESO/R. Hurt)

- Mass:
  - Dark matter mass within ~ 250 kpc $\sim 10^{12} M_{\odot}$
  - Baryonic mass $\sim 10^{11} M_{\odot}$
- Visible mass:
  - Disk + bulge = 99%
  - Stellar halo = 1%
  - Stellar halo = $\sim$ 1% globular clusters + 99% stars
- Halo stars: old, metal-poor, large random motions



Milky Way stellar halo

- Motivation to study the stellar halo:
  - Galaxy formation
  - Properties of the old stellar populations
  - Remnants of past mergers
  - Test cosmological models
  - Probe the dark matter halo



Key questions related to stellar halo investigations

- What mechanisms form the halo and at what time? Early on during initial formation of the galaxy? Later on by accreted galaxies?
- How do the kinematics and chemistry evolve with time?
- How do halos differ between different galaxies?
- What causes bumps and wiggles in the Milky Way's stellar halo kinematics?
- How many accreted objects have contributed to the build up our Galaxy?
- What is the mass of the Galaxy?

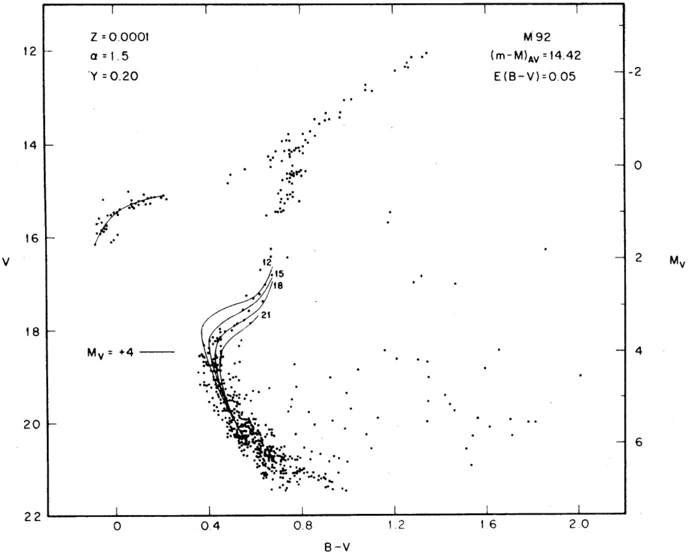
Milky Way stellar halo properties[1,2]

Typical values for	inner halo	outer halo
Galactocentric radius[4]	< 20 kpc	> 20 kpc
age[1]	> 10 Gyr	> 10 Gyr
peak metallicity [Fe/H][3,4]	-1.6 dex	-2.2 dex
metallicity range [Fe/H][3]	$-4.0 - 0$ dex	$-4.0 - 0$ dex
spatial distribution[4]	flattened	spherical
n, density profile[4−7] $\rho \propto r^{-n}$	2-4	2-4
kinematics[8,9,10,11]	radial+wiggle	isotropic to radial
Galactic radial velocity dispersion[11,12,13]	120 km/s	declines to 50 km/s

[1]Helmi 2008, [2]Bland-Hawthorn & Gerhard 2016, [3]Ryan & Norris 1991, [4]Carollo+07,10,12, [5]Deason+11, [6]Gnedin+10, [7]Xu+17, [8]Sommer-Larsen+97, [8]Kafle+12,[10]Deason+13, [11]Kafle+14, [12]Battaglia+05,06, [13]Deason+12

Useful tracers of halo star dynamics Figure: Sandage83

- G and K giant
- RR Lyrae
- Blue horizontal branch



Stellar tracers of the halo

Tracer Star	Number	Distance Range [kpc]	Survey	Reference
K giant	6900	3 – 200	LAMOST	Bird+17
K giant	6036	5 – 125	SDSS/SEGUE	Xue+14
BHB[1]	4664	5 – 60	SDSS/SEGUE	Kafle+12
BHB	1933	16 – 48	SDSS/SEGUE	Deason+12
BHB	4985	5 – 80	SDSS/SEGUE	Xue+11
BHB	3549	10 – 50	SDSS/SEGUE	Deason+11
BHB	666	20 – 100	2QZ Redshift Survey	De Propris+10
A-type	910	15 – 75	Hypervelocity Star Survey	Brown+10
BHB	2558	5 – 60	SDSS/SEGUE	Xue+08
BHB	1170	5 – 96	SDSS/SEGUE	Sirko+04
BHB	700	< 45	mixture of surveys	Sommer-Larsen+97

[1] blue horizontal branch

Collecting more Milky Way halo stars!

LAMOST Photo Gallery

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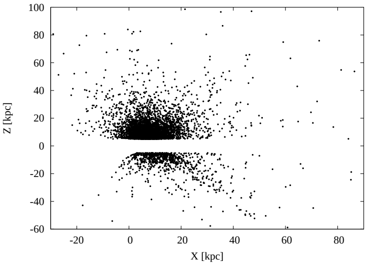
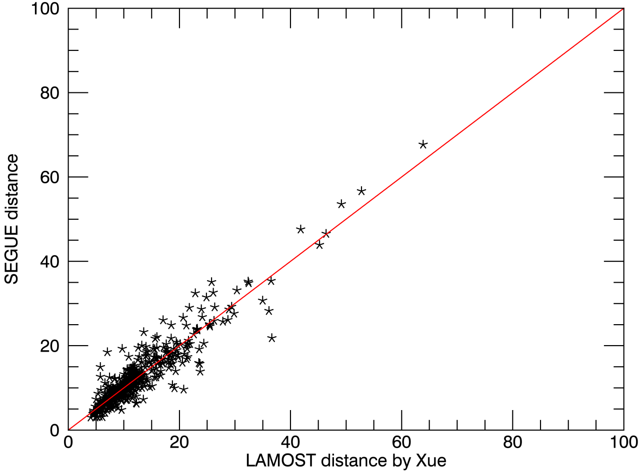
Galactic K-giant halo stars from LAMOST

Selection criteria:

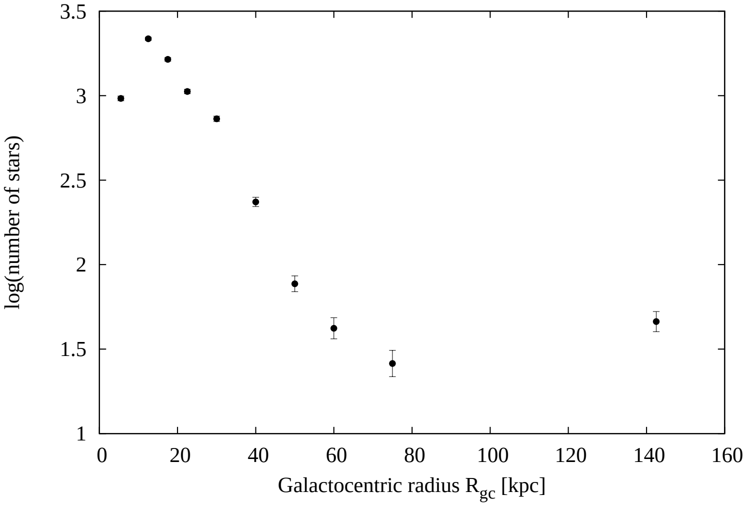
- LAMOST Data Release 3
- 4000 $< \mathrm{T_{eff}}/\mathrm{K} <$ 5600
- surface gravity $\log \mathrm{g} <$ 4 dex
- exclusion of red clump stars based on $\mathrm{Mg_b}$ lines Liu+14
- distance using method of Xue+14
- $|\mathrm{Z}| >$ 5 kpc
- $[\mathrm{Fe/H}] < -$1.3 dex
- total: over 6900 K-giant spectra out to $R_{\mathrm{gc}} =$ 200 kpc



Halo K-giant matches: LAMOST vs SEGUE (Xue+14)



Number histogram of LAMOST halo K giants



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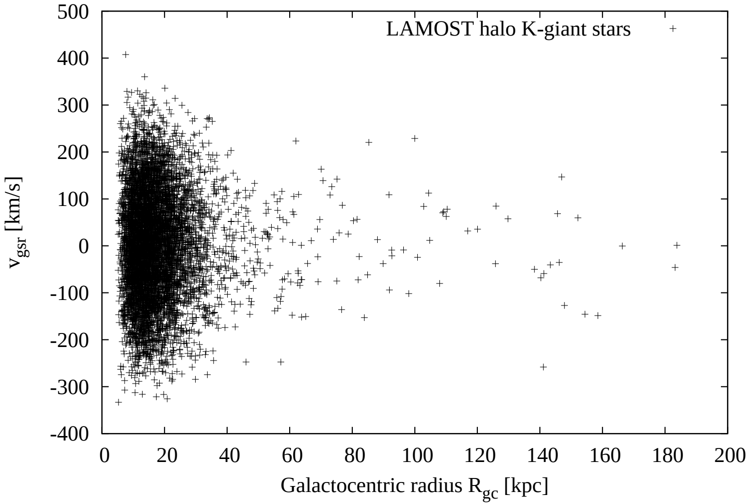
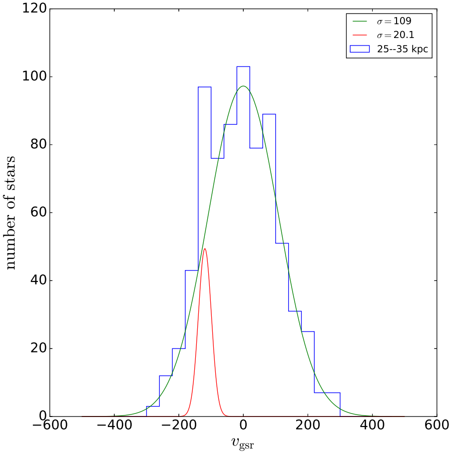
Line-of-sight velocity of LAMOST halo K giants



Velocity histograms with LAMOST

Double Gaussian fit:

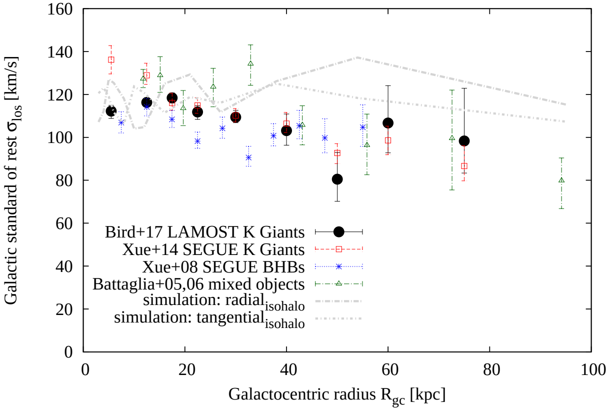
- broad Gaussian: smooth distribution of halo stars
- narrow Gaussian: stellar stream
- remove streams from further analysis



Line-of-sight velocity dispersion: observations

Comparison between different studies:

- consistent results
- flattened profile



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Jeans equation and virial theorem

- Jeans equation describes the motion of a collection of tracer particles in a galactic potential $\frac{\mathrm{d}\Phi}{\mathrm{d}r}$

$$\frac{\mathrm{d}}{\mathrm{d}r}(\nu\sigma_r^2) + \frac{2\beta}{r}\nu\sigma_r^2 = \nu\frac{\mathrm{d}\Phi}{\mathrm{d}r}$$

  - σ_{r} radial and σ_{t} tangential velocity dispersion profile
  - anisotropy parameter $\beta = 1 - \frac{\sigma_\theta^2+\sigma_\phi^2}{2\sigma_r^2} = 1 - \frac{\sigma_t^2}{\sigma_r^2}$
  - ν density profile of particles
- Virial theorem describes the system as a whole, relating together the average over time of the kinetic and potential energies. For example the system here is a galaxy.

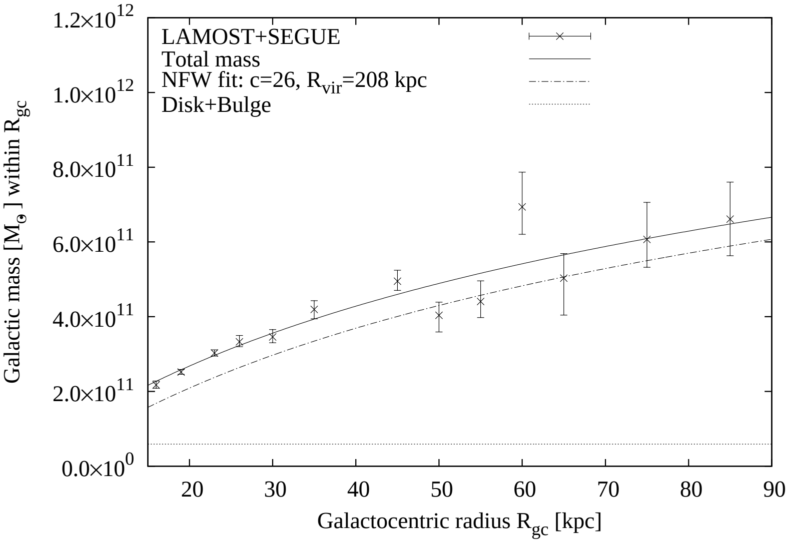
$$\langle v^2 \rangle = \left\langle \frac{GM}{r} \right\rangle$$

Tracer mass estimator Evans+11

$$M_{\rm out} \approx \frac{r_{\rm out}^{0.5}(0.5+\gamma-2\beta)}{GN}\sum_{i=1}^{N} r_i^{0.5} v_{r,i}^2$$

- Estimates mass $M_{\rm out}$ out to the distance $r_{\rm out}$ of the furthest data point
- Observations of N number of halo tracers
  - radial velocity v_r
  - galactocentric distance r
- Assumptions
  - simplest case dynamics: spherical system traced by a non-rotating relaxed population in equilibrium
  - Navarro-Frenk-White dark halo density profile
  - tracer number density $\propto r^{-\gamma}$ with $\gamma \approx 4$ Xu+17
  - velocity isotropy ($\beta = 0$)

Milky Way mass profile: LAMOST + SEGUE



Results from tracer mass estimator Evans+11

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

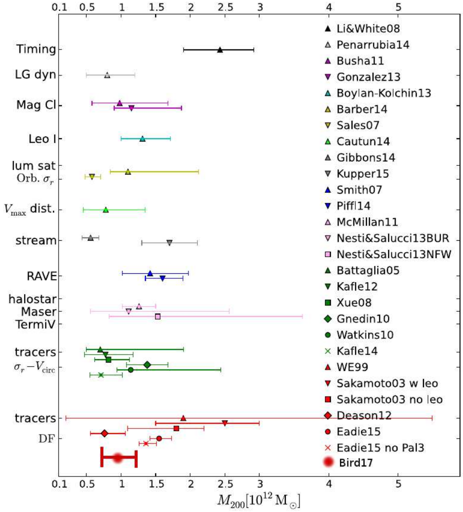
- total number of tracers $N = 5734$ K giants
- Milky Way mass out to 85 kpc: $0.7 \pm 0.1 \times 10^{12} \mathrm{M}_\odot$

Extrapolate mass out to the virial radius $r_{\rm vir}$

- 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: $r_{\rm vir} = 208$ kpc and concentration $c = 26$
- $\Rightarrow$ result: $M(r_{\rm vir}) = 0.9^{+0.6}_{-0.3} \times 10^{12} \mathrm{M}_\odot$
- Comparable mass to Huang+16

Results: Galactic mass compared

Figure: adapted from Wang15



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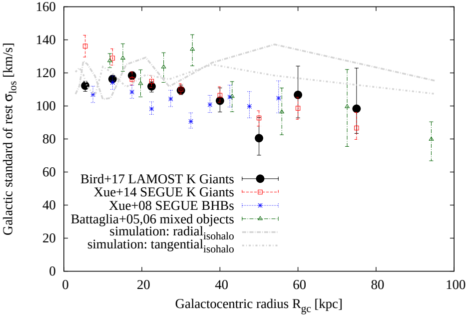
Thanks!

Summary and Future Work:

- Flattened velocity dispersion profile
- Galactic mass estimate with LAMOST+SEGUE
- Run simulations: check v_{los} vs v_{r}
- Collect more halo stars with LAMOST



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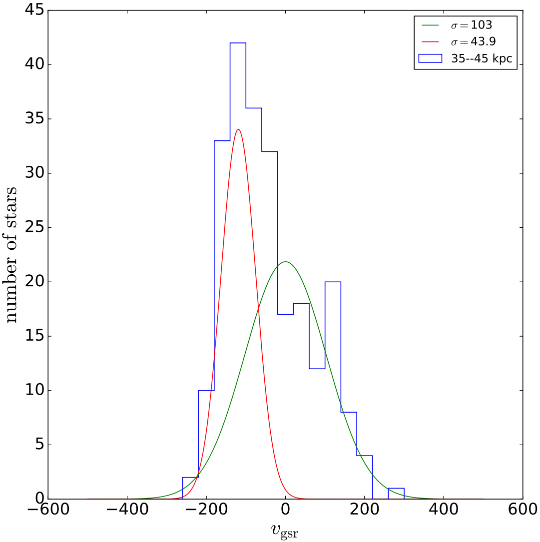
Velocity histograms with LAMOST



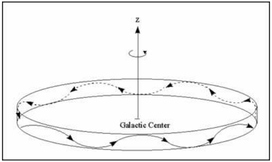
Mass Estimator for Navarro-Frenk-White Halos

- Evans, An, Deason 2011
- Mass estimator uses halo tracers
- Assumes a Navarro-Frenk-White dark halo density profile
- $$\rho(r) \propto \frac{1}{r(a+r)^2}$$
- scale radius a and is related to the concentration parameter $c = r_{\rm vir}/a$

Galactic Mass

- Extrapolate mass out to virial radius
- Navarro-Frenk-White Halo for mass within radius r
- $$M(r) = 4\pi\rho_0 a^3 \ln(1 + r/a) - \frac{r/a}{1 + r/a}$$
- ρ_0 is a density parameter, a is scaling radius
- $a = r_{\rm vir}/c$
- c is concentration

Galactic kinematics and velocity dispersion



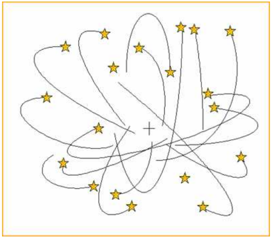


Figure : disk and halo

$$\sigma = \sqrt{\frac{\sum (x_i - \overline{x})^2}{N-1}}$$

Line-of-sight velocity dispersion: observations