Milky Way's Mass and Stellar Halo Velocity Dispersion Profiles

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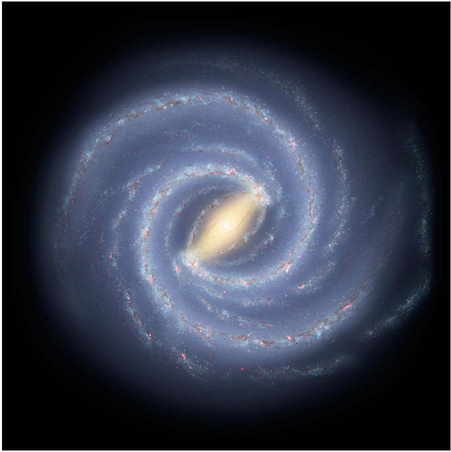
Contents

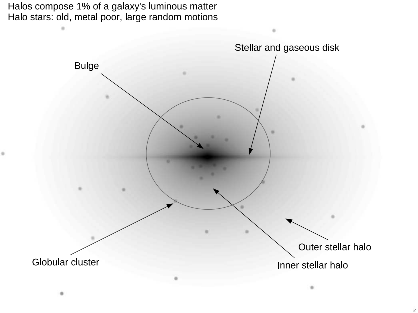
The Milky Way (Bland-Hawthorn & Gerhard 2016, Helmi 2008, Figure: NASA/JPL-Caltech/ESO/R. Hurt)

- Mass:
  - Dark matter mass within ~ 250 kpc $\sim 10^{12} M_{\odot}$
  - Visible 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:
  - Constrain galaxy formation
  - Properties of the old stellar populations
  - Find remnants of past mergers
  - Test cosmological models
  - Probe the dark matter halo



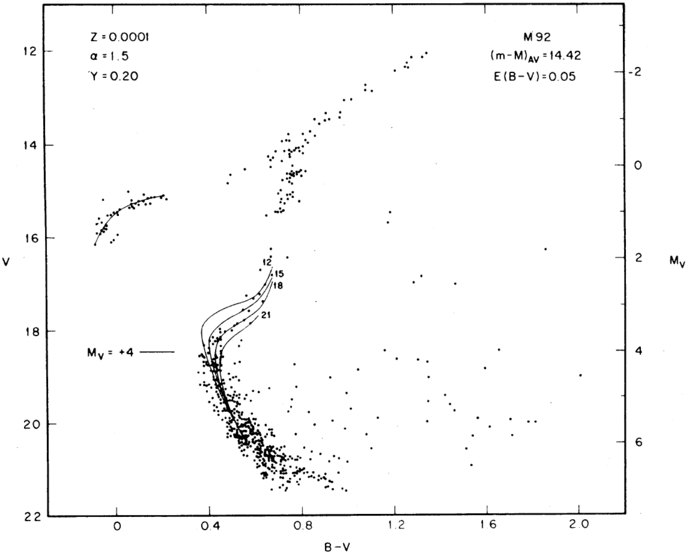
Milky Way stellar halo properties[1,2]

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]	$-4 - 0$ dex	$-4 - 0$ 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, [9]Kafle+12,[10]Deason+13, [11]Kafle+14, [12]Battaglia+05,06, [13]Deason+12

Useful tracers of halo star kinematics Figure: Sandage83

- giant stars
- RR Lyrae
- blue horizontal branch stars



Stellar tracers of the halo

Tracer Star	Number	Distance Range [kpc]	Survey	Reference
K giant	6900	5 – 180	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!

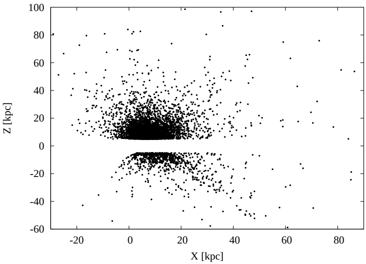
LAMOST Photo Gallery

Contents

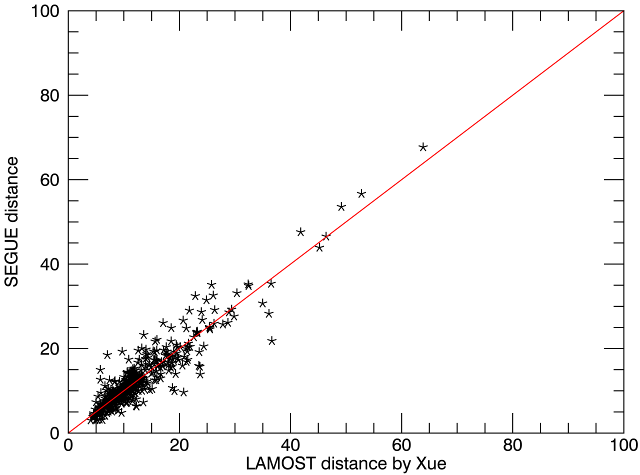
Galactic K-giant halo stars from LAMOST

Selection criteria:

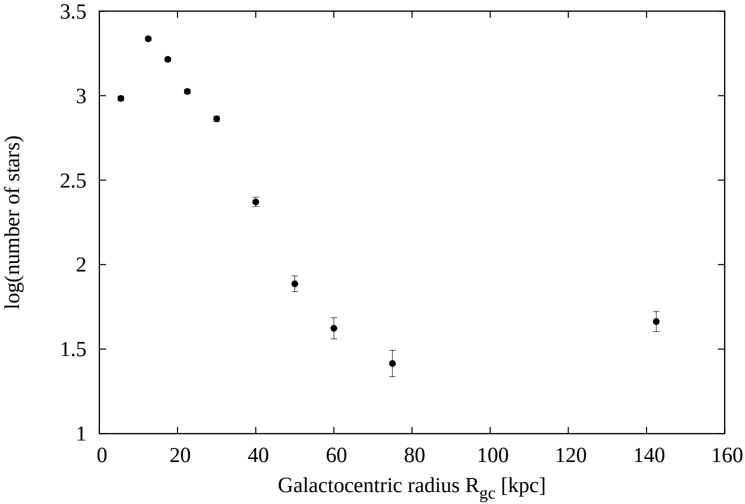
- LAMOST Data Release 3
- $4000 < \mathrm{T_{eff}/K} < 5600$
- surface gravity $\log \mathrm{g} < 4$ dex
- exclusion of red clump stars based on $\mathrm{Mg_b}$ lines Liu+14
- distance using method of Xue+14
- $|\mathrm{Z}| > 5$ kpc
- $[\mathrm{Fe/H}] < -1.3$ dex
- total: over 6900 K-giant spectra out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



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

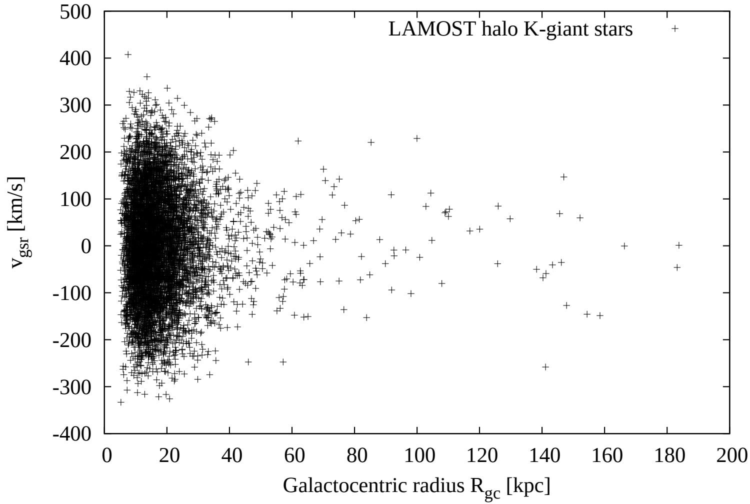


Number histogram of LAMOST halo K giants



Contents

Line-of-sight velocity of LAMOST halo K giants

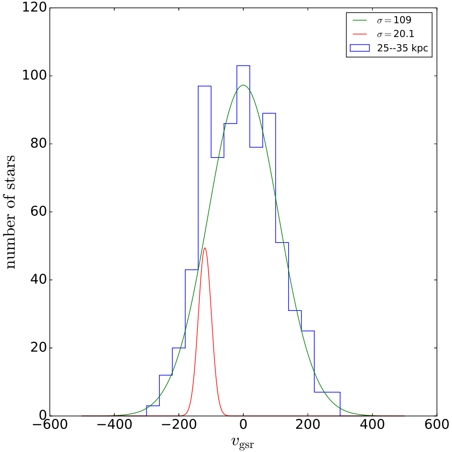


Velocity histograms with LAMOST

Use velocities to exclude streams

Double Gaussian fit:

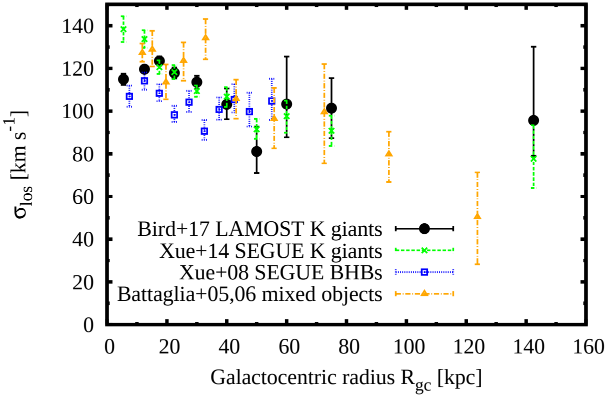
- broad Gaussian: smooth distribution of halo stars
- narrow Gaussian: stellar stream
- remove streams from further analysis
- if amplitude of narrow Gaussian is smaller than 10% of the broad Gaussian, refit with a single Gaussian



Line-of-sight velocity dispersion: observations

Comparison between different tracer samples:

- consistent results
- flattened profile



Contents

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.

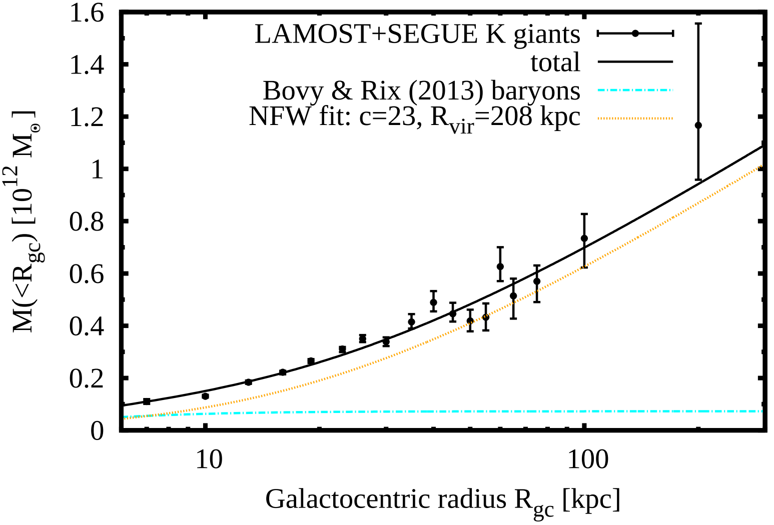
$$\langle v^2 \rangle = \left\langle \frac{GM}{r} \right\rangle$$

Tracer mass estimator Evans+11

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

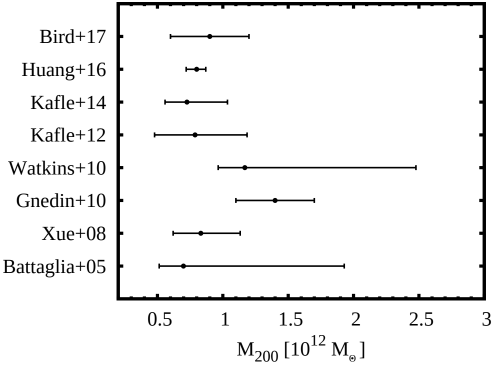
- Estimates mass $M_{\rm out}$ out to the distance $r_{\rm out}$ of the furthest data point
- Observations of N number of halo tracers
  - radial velocity v_r
  - galactocentric distance r
- Assumptions
  - simplest case dynamics: spherical system traced by a non-rotating relaxed population in equilibrium
  - 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

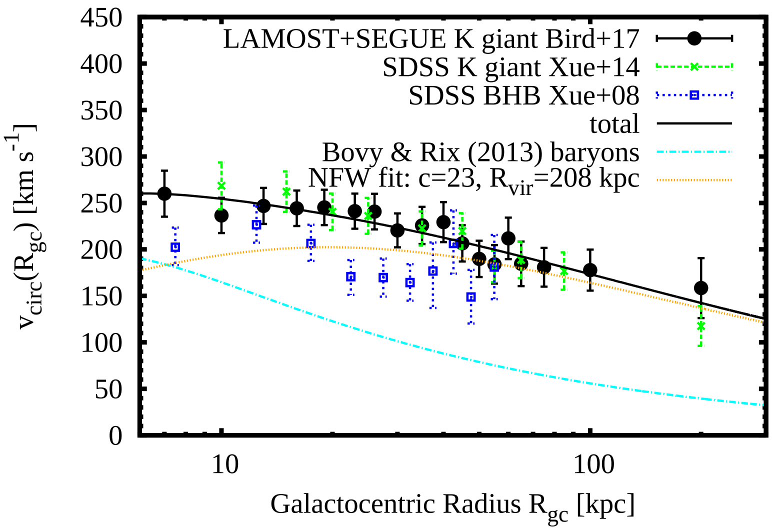


Milky Way mass: LAMOST + SEGUE

- LAMOST contributes to over half our sample
  - $5 < R_{\rm gc}/{\rm kpc} < 200$
  - over 10,000 K giants
- NFW fit:
  - $r_{200} = 210 \pm 16$ kpc
  - concentration $c = 23 \pm 5$
  - $M_{200} = 0.9 \pm 0.3 \times 10^{12} {\rm M}_\odot$
- figure: Bird+17, adapted from Wang+15



Milky Way circular velocity profile

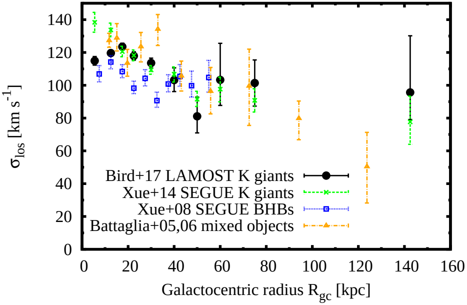


Contents

Thanks!

Summary:

- LAMOST contributes to over half our sample of $> 10^4$ K-giants
- Flattened velocity dispersion profile
- Galactic mass estimate with LAMOST+SEGUE
- Galactic circular velocity profile with LAMOST+SEGUE
- Collect $\sim 10^4$ halo stars with LAMOST
- Combine LAMOST+*Gaia* to measure 3D velocities



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