Milky Way mass with K giants and BHB stars using LAMOST, SDSS/SEGUE, and *Gaia*: 3D spherical Jeans equation and tracer mass estimator

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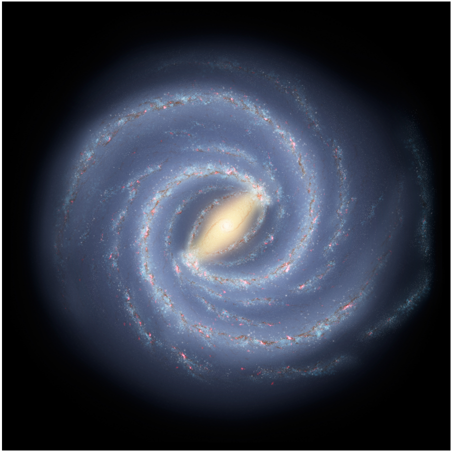
The Milky Way

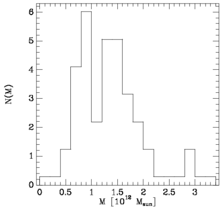
Bland-Hawthorn & Gerhard 2016, Helmi 2008, Figure: NASA/JPL-Caltech/ESO/R. Hurt

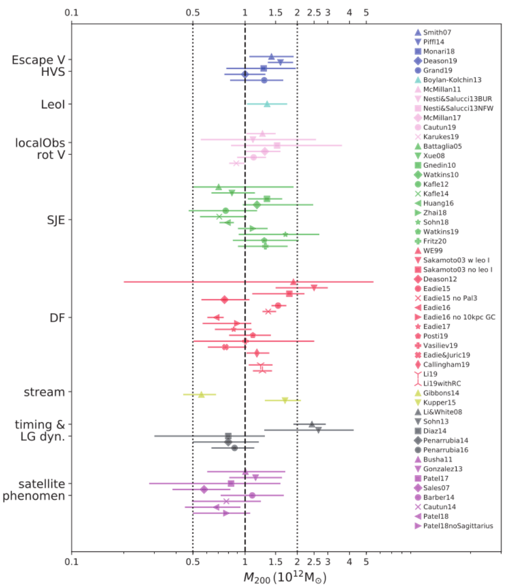
- Mass:
  - Dark matter mass within ~ 250 kpc $\sim 10^{12} M_{\odot}$
  - Visible mass $\sim 10^{11} M_{\odot}$
- Visible mass:
  - Disk + bulge = 99%
  - Stellar halo = 1%
  - Stellar halo = ~ 1% globular clusters + 99% stars
- Halo stars: old, metal-poor, large random motions



Galactic mass Figure:Wang+20, see also Callingham+19,Wang+15,Eadie&Harris16,19

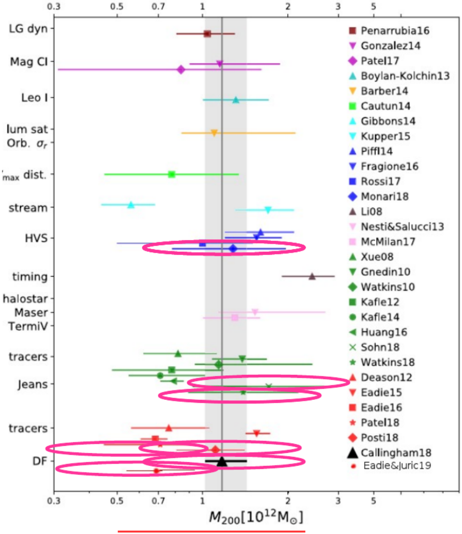
- recent estimates using tracers: satellites, globular clusters, halo stars
- virial mass M_{200} is the enclosed mass within a spherical region with mean density equal to 200 times the critical density of the Universe
- range of mass estimates over a factor of four, covered by the figure is a 40% scatter!





Galactic mass Figure from Callingham+19, also see Wang+20,15,Eadie&Harris16,19

- ellipses mark most recent estimates using *Gaia* DR2, Hubble Space Telescope, or other high quality proper motions
- large scatter of mass estimates remains
- still an ongoing effort to minimize mass uncertainties



Method 1: 3D spherical Jeans mass

- The spherical Jeans equation relates the kinematics and density profile of a collection of tracer particles to the enclosed mass within radius r, $M(< r)$, as

$$M(< r) = -\frac{1}{G}(r^2 \frac{d\sigma_r^2}{dr} + r(\sigma_r^2(2+\alpha) - \sigma_\theta^2 - \sigma_\phi^2))$$

  - $(\sigma_r, \sigma_\theta, \sigma_\phi)$ velocity dispersion in spherical coordinates (radial, polar, azimuthal) modelled as a 3D Gaussian in the 3D velocity space including correct modelling of the differing velocity errors
  - α power law assuming density of particles $\propto r^{-\alpha}$
  - assumes a virialized system

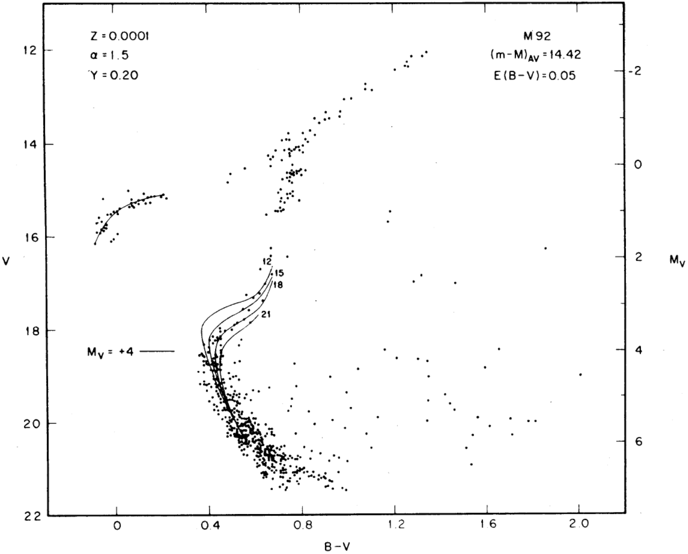
Method 2: tracer mass estimator Evans+11

$$M_{\rm out} \approx \frac{r_{\rm out}^{0.5}(0.5+\alpha-2\beta)}{GN}\sum_{i=1}^{N} r_i^{0.5}(V_{r,i}-\langle V_r\rangle)^2$$

- 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
  - velocity anisotropy $\beta = 1-(\sigma_\theta^2+\sigma_\phi^2)/(2\sigma_r^2)$
  - α power law assuming density of particles $\propto r^{-\alpha}$
- Subtract mean $\langle V_r\rangle$ to correct for effects of LMC Erkal+2020

Useful tracers of halo star kinematics Figure: Sandage83

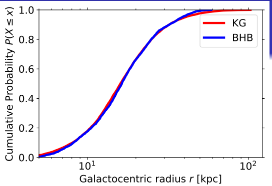
- giant stars
- RR Lyrae
- blue horizontal branch stars

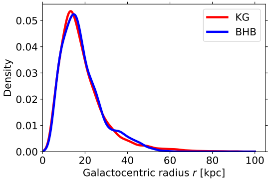


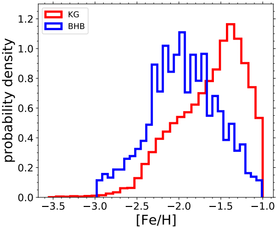
Smooth, diffuse Galactic halo sample

- SDSS/SEGUE+LAMOST DR5+*Gaia* DR2
- **K giants**
  - LAMOST: defined by $T_{\rm eff}$ and $\log g$

    Liu+14
  - SDSS/SEGUE: defined as in Xue+14
  - spectroscopic distances Xue+14
- **Blue horizontal branch (BHB)** Xue+08
  - limits in color and Balmer line profile
  - photometric distances
- $|Z| > 2$ kpc & $[\mathrm{Fe/H}] < -1$
- (V_r, V_θ, V_ϕ):
  - $V < 500$ km s^{-1}
  - $\delta V < 150$ km s^{-1}
- subtructure removal by integrals-of-motion
- **total: 10762 K giants and 2526 BHBs**



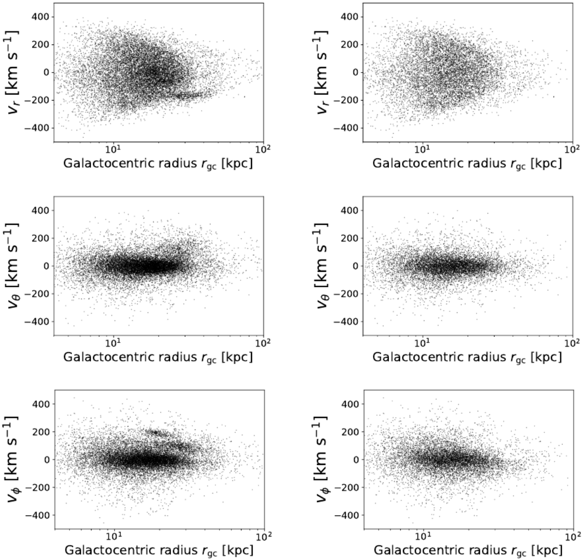




Substructure removal Xue+in prep.

Selection criteria:

- stellar halo substructure in integral-of-motion space using friends-of-friends
- 4 integrals of motion: E, Lx, Ly, Lz
- determine orbital parameters: $e, a, (l_{\rm orbit}, b_{orbit}), l_{\rm apo}$
- stream-members share similar orbits



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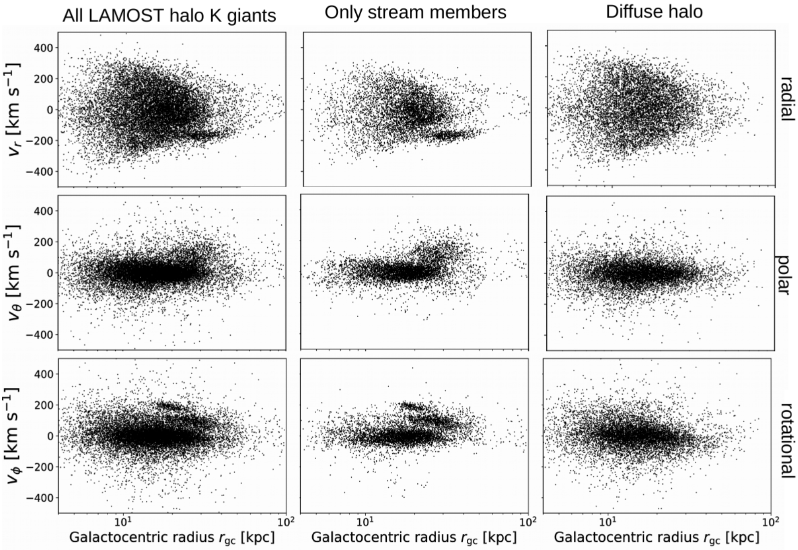
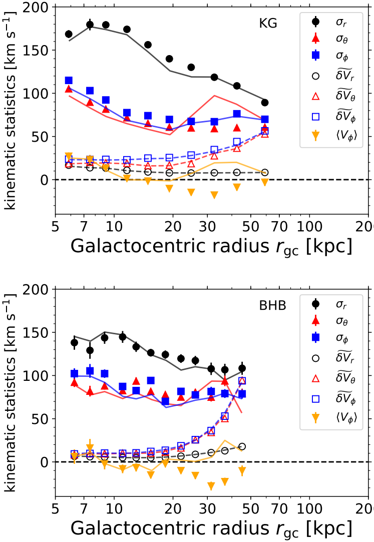


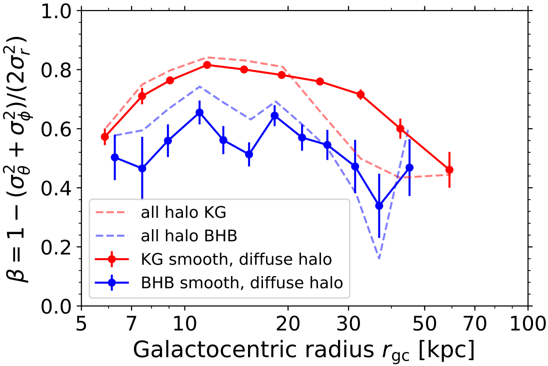
Kinematic statistics vs r_{gc}

- $\sigma_r > \sigma_\theta, \sigma_\phi$ at all r_{gc}
- 3D velocity dispersion profiles dropping for $r_{\mathrm{gc}} < 20$ kpc
- evidence of Sagittarius stream $r_{\mathrm{gc}} > 20$ kpc
- median velocity uncertainty $\widetilde{\delta V_r}, \widetilde{\delta V_\theta}, \widetilde{\delta V_\phi}$: open markers
- mean rotational velocity $\langle V_\phi \rangle$: orange markers
- all stars: lines. diffuse halo: markers
- LAMOST/SDSS K giants: upper
- SDSS BHB stars: lower
- each marker represents the median distance of binned stars



Velocity anisotropy β

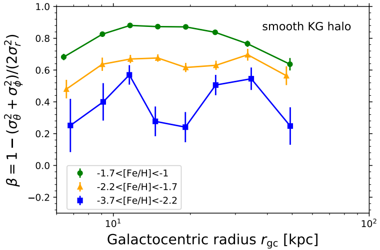
- highly radial within $r_{\rm gc} < 30$ kpc
- gently falls to lower radial values for $r_{\rm gc} > 30$ kpc
- LAMOST/SDSS K giants: red
- SDSS BHB stars: blue
- each marker represents the median distance of binned stars

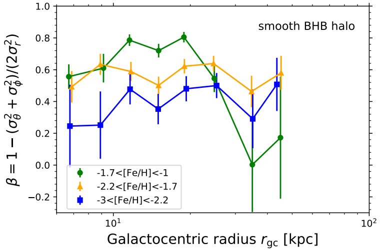


Velocity anisotropy and [Fe/H]

β for LAMOST/SEGUE K giants compared with SDSS BHB's in common metallicity bins after stream removal:

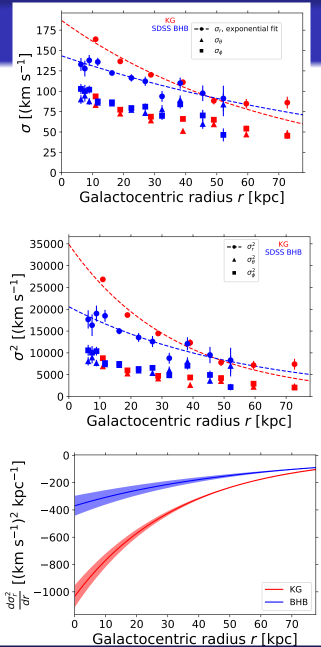
- similar β profile
- similar β dependency on metallicity
- distance and metallicity determinations are in concordance





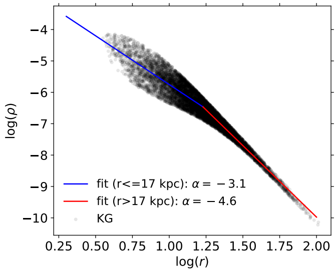
Velocity terms for Jeans equation

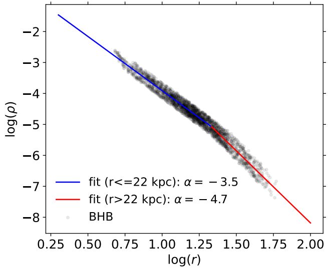
- σ (upper): dashed lines are an exponential fit
- σ^2 (middle)
- (V_r, V_θ, V_ϕ) components are (circle, triangel, square) markers
- $\frac{d\sigma_r^2}{dr}$ (lower): gradient of exponential fit to σ_r
- LAMOST/SDSS K giants: red
- SDSS BHB stars: blue
- KG and BHB differ most in V_r components



Stellar halo density profile

- broken power law density $\rho(r)$ profile fits in spherical shells along Galactocentric radius r
- Xu+2018 and Das+2016 density models
- using $\alpha_{\rm in} = -3.1$ leads to circular velocity > 250 km s^{-1} near the Sun for our KG sample
- adjust our selected value for KG stars to $\alpha_{\rm in} = -2.8$ which gives $v_{\rm circ} < 250$ km s^{-1} near the Sun
- Results:
  - similar $\alpha_{\rm out} = -4.6, -4.7$
  - KG more flattened $\alpha_{\rm in} = -2.8$ than BHB $\alpha_{\rm in} = -3.1$

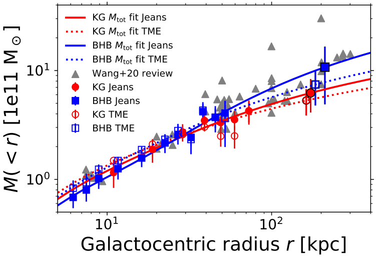


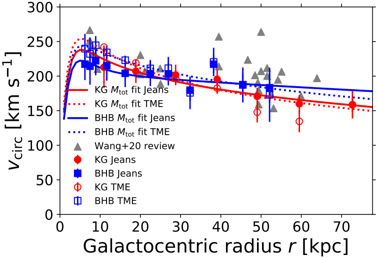


Galactic mass: Jeans and tracer mass estimator

- 3D spherical Jeans enclosed mass estimate (filled markers)
- tracer mass estimator Evans+11 (open markers)
- LAMOST K giants (red) and SDSS/SEGUE BHB stars (blue)
  - smooth halo kinematics
  - density profile from literature

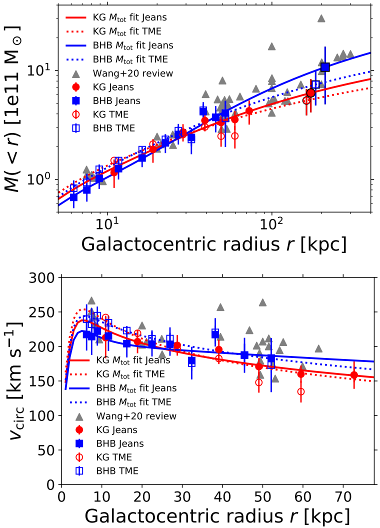
  Xu+18, Das+16
- Good agreement in mass measured from two methods and two star types





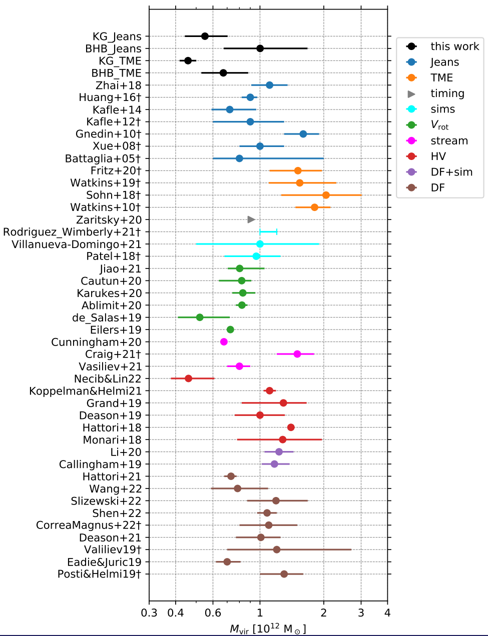
Galactic mass model fit

- disk & bulge Bovy+13,15 NFW dark matter
- Results:
  - $M(< r)$ fit for Jeans (solid line) and TME (dotted line)
  - most distant mass markers correspond to total mass M_{tot} estimates within the virial radius r_{200} from the model fits
  - dark matter mass M_{200} $[\times 10^{12}\ \mathrm{M}_{\odot}]$: 0.55 (KG Jeans), 1.00 (BHB Jeans), 0.46 (KG TME), and 0.67 (BHB TME)
  - weighted average$\pm$(random and systematic uncertainties): $M_{200} = 0.53 \pm 0.10 \times 10^{12}\ \mathrm{M}_{\odot}$, $r_{200} = 172 \pm 27$ kpc, $c = 20 \pm 5$
- gray triangles are from literature Wang+20



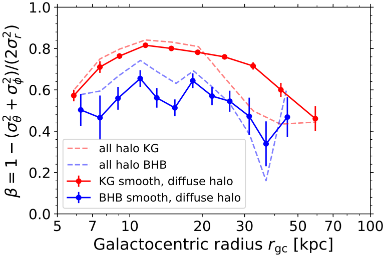
Virial Mass

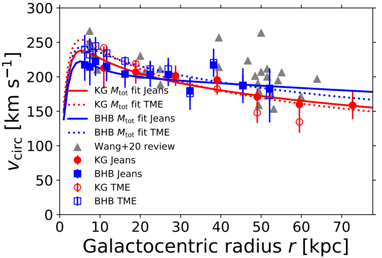
- our dark matter estimates from Jeans and TME (black)
- recent M_{vir} from literature
- total weighted average virial mass from most recent studies: $\sim 0.85 \times 10^{12}$ M$_\odot$ with a scatter of $\sim 33\%$



Key Conclusions and Discoveries

- LAMOST/SDSS + *Gaia* DR2 yield $>$ 13000 smooth, diffuse halo K-giant and BHB stars
- first presentation of **3D velocity profiles** for such a large and far-reaching halo star sample!
- K giants and BHB's both share similar:
  - **radially dominated** stellar orbits
  - β **dependence on [Fe/H]**
- consistent mass estimates between two methods and two star types
- weighted average$\pm$(random and systematic uncertainties): $M_{200} = 0.53 \pm 0.10 \times 10^{12}$ M$_{\odot}$, $r_{200} = 172 \pm 27$ kpc, $c = 20 \pm 5$





Topics for discussion

- $M_{\rm vir} = 0.85 \times 10^{12} \rm M_{\odot}$ weighted average with a scatter of 33% of the most recent mass estimates, but is there method that is intrinsically better than others?
- What questions can addressed using $M_{\rm vir}$ with 33% scatter? What questions do we still need quite better accuracy?
- What can we do to more accurately measure the mass now, instead of waiting till the next SuperGaia?

Thanks!!!

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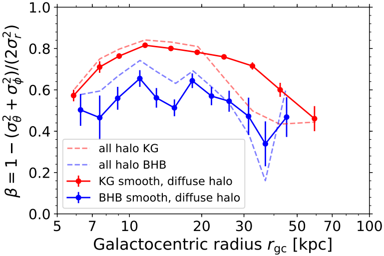

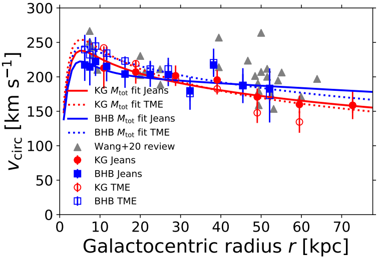

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