Galactic Mass and Anisotropy Profile with Halo K-Giant and Blue Horizontal Branch Stars from LAMOST/SDSS and *Gaia*

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Self-introduction

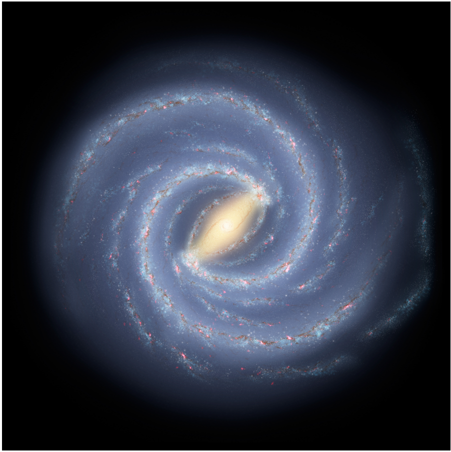
Sarah Ann Bird

Education
B.S. in Physics
  University of Missouri, USA, 2007
Ph.D. in Astronomy
  University of Turku, Finland, 2014
LAMOST Fellow
  Shanghai Astronomical Observatory, 2014-2015
PIFI Fellow
  Shanghai Astronomical Observatory, 2016-2018
Aliyun Fellow
  National Astronomical Observatories of China, Beijing, 2019-2020
CTGU Faculty, Yichang, China, 2021-present

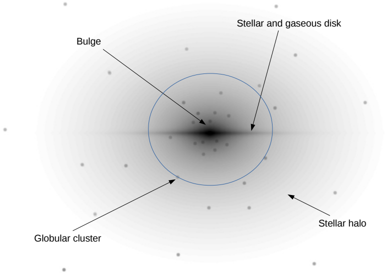
Research Expertise
Optical and spectroscopic observations
Galactic kinematic-simulations using potential theory
Galaxy halos
Galaxy formation and evolution

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

- Mass:
  - Dark matter mass within < 200 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

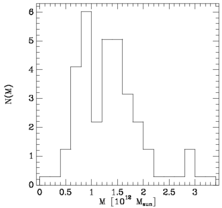


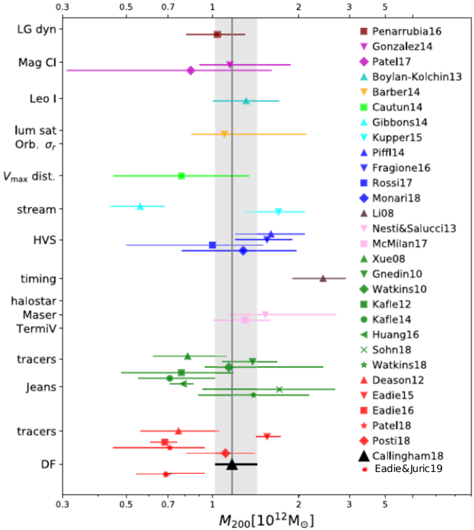
- Motivation to study the stellar halo:
  - Constrain galaxy formation
  - Properties of the old stellar populations
  - Find remnants of past mergers
  - Test cosmological models
  - Probe the dark matter halo



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

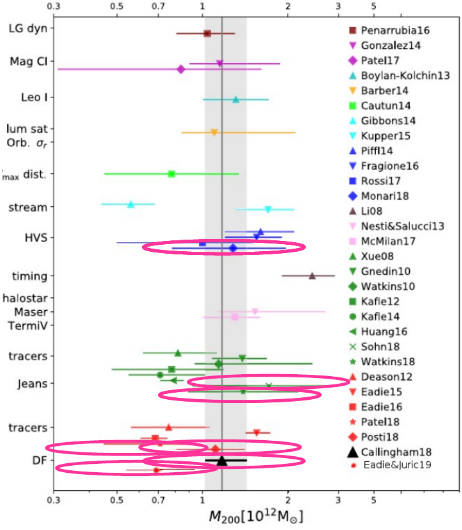
- recent estimates using tracers: satellites, globular clusters, halo stars
- virial mass M_{200} is the enclosed mass within a spherical region with mean density equal to 200 times the critical density of the Universe
- range of mass estimates over a factor of four, covered by the figure is a 40% scatter!





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



Spherical Jeans equation

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

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

  - $(\sigma_r, \sigma_\theta, \sigma_\phi)$ velocity dispersion in spherical coordinates (radial, polar, azimuthal)
  - anisotropy parameter $\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$
  - ν space density of particles
  - assumes a virialized system

Stellar density profiles ν table from Xu+2018

Table 1. Incomplete list of recent stellar halo profile fits.

Reference	Origin	Tracer	Sample size	Distance(kpc)	Model	Parameters
Iorio et al. (2017)	GAIA+2MASS	RR Lyrae	21600	$R < 28$	Triaxial	$n = 2.96$, $p = 1.27$, $q = f(r)$, $q_0 = 0.57$, $q_{\inf} = 0.84$, $r_0 = 12.2$ kpc
Das et al. (2016)	SEGUE2	BHB		$r_{GC} < 70$	BPL	$n_{in} = 3.61$, $n_{out} = 4.75$, $r_{break} = 29.87$, $q = 0.72$
					SPL	$n = 4.65$, $q = f(r_{GC})$, $q_0 = 0.39$, $q_{\inf} = 0.81$, $r_0 = 7.32$ kpc
X15	SEGUE2	K giants	1757	$10 < r_{GC} < 80$	BPL	$n_{in} = 2.8$, $n_{out} = 4.3$, $r_{break} = 29$, q $= 0.77$
					Einasto	$n = 2.3$, $r_{eff} = 18$, $q = 0.77$
					SPL	$n = 4.4$, $q = f(r_{GC})$, $q_0 = 0.3$, $q_{\inf} = 0.9$, $r_0 = 9$ kpc
Pila-Diez et al. (2015)	CFHTS and INT	Near MSTO		$r_{GC} < 60$	SPL	$n = 4.3$, $q = 0.79$
					Triaxial	$n = 4.28$, $q = 0.77$, $\omega = 0.87$
					BPL	$n_{in} = 2.4$, $n_{out} = 4.8$, $r_{break} = 19$, $q = 0.77$
					BPL_q	$n_{in} = 3.3$, $n_{out} = 4.9$, $q_{in} = 0.7$, $q_{out} = 0.88$
Deason et al. (2011)	SDSS DR8	BS,BHB	~20 000	$4 < D < 40$	BPL	$n_{in} = 2.3$, $n_{out} = 4.6$, $r_{break} = 27$, $q = 0.6$
Deason et al. (2014)	SDSS DR9	BS,BHB		$10 < D_{BS} < 75$ $40 < D_{BHB} < 100$	BPL	$n_{outer} = 6 - 10$, $r_{break} = 50$
Watkins et al. (2009)	Stripe82	RRly	417	$5 < r_{GC} < 117$	BPL	$n_{in} = 2.4$, $n_{out} = 4.5$, $r_{break} = 25$
Sesar et al. (2011)	CFHTLS	near MSTO	27 544	$D < 35$	BPL	$n_{in} = 2.62$, $n_{out} = 3.8$, $r_{break} = 28$, $q = 0.7$
Juric et al. (2008)	SDSS	MS		$D < 20$	SPL	$n = -2.8$, $q = 0.64$
Bell et al. (2008)	SDSS	MS	4 million	$D < 40$	SPL	$2 < n < 4$, $0.5 < q < 0.8$
Siegel et al. (2002)	Kapteyn		70 000		SPL	$n = 2.75$, $q = 0.6$
Robin et al. (2000)	PB				SPL	$n = 2.44$, $q = 0.76$

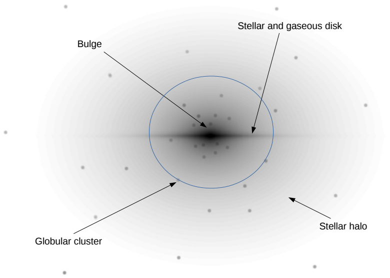
Notes. CFHTLS (Canada–France–Hawaii Telescope Legacy Survey); near MSTO (near main-sequence turnoff stars); INT (Isaac Newton Telescope); PB (pencil beams from different observations); and Kapteyn (seven Kapteyn selected areas).

stellar halo space density profiles are generally well fit by some form of a power law distribution

Velocity anisotropy β Binney 1980; Binney & Tremaine 2008

$$\beta = 1 - (\sigma_\theta^2 + \sigma_\phi^2)/(2\sigma_r^2)$$

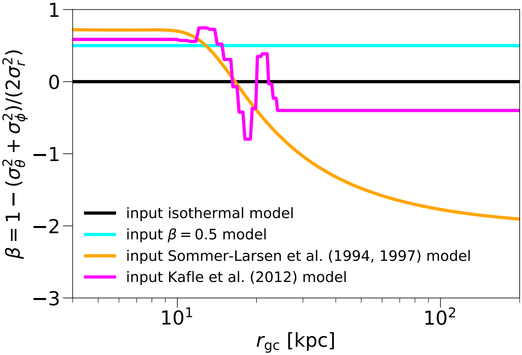
- isotropic ($\beta = 0$)
- radial ($0 < \beta < 1$)
- tangential ($-\infty < \beta < 0$)
- estimate the mass of the Milky Way through the Jeans equation
- clues to galaxy formation from halo stars
  - orbits have long dynamical time scales
  - collisionless system
  - orbital shapes are relatively immune to adiabatic change of the gravitational potential



Velocity anisotropy β profile (Pre-*Gaia* DR2)

β profile as seen by

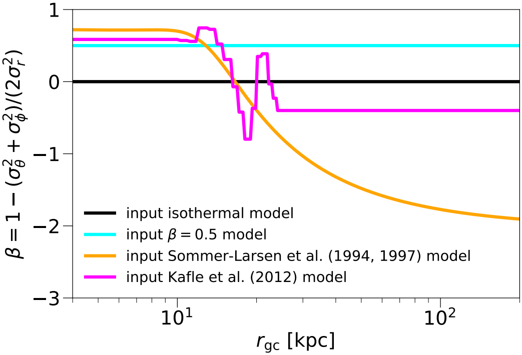
- Simulations: slowly rising radially e.g. Diemand+05, Abadi+06, Sales+07, Rashkov+13, Loebman+18



Velocity anisotropy β profile (Pre-*Gaia* DR2)

β profile as seen by

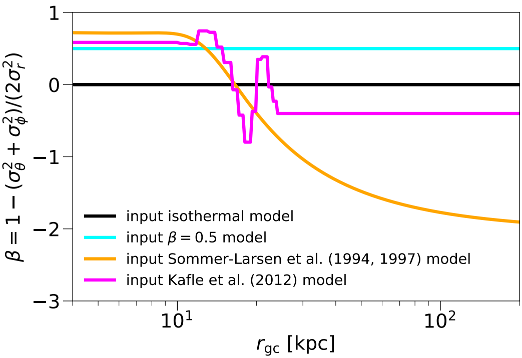
- Simulations: slowly rising radially
- Solar neighborhood: $0.5 < \beta < 0.7$ e.g. Chiba&Yoshii98, Chiba&Beers2000, Smith+09, Bond+10



Velocity anisotropy β profile (Pre-*Gaia* DR2)

β profile as seen by

- Simulations: slowly rising radially
- Solar neighborhood: $0.5 < \beta < 0.7$
- Observations past 15 kpc: variety of differing results!!!
  - Direct: Cunningham+16,18
  - Indirect: Sommer-Larsen+94, Wilkinson&Evans99, Sirko+04, Thom+05, Kafle+12,14,17, Deason+12,13, King+15, Williams&Evans15



Velocity anisotropy β profile (Pre-*Gaia* DR2)

β profile as seen by

- Simulations: slowly rising radially
- Solar neighborhood: $0.5 < \beta < 0.7$
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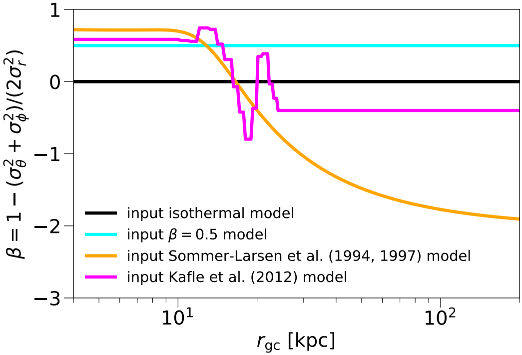
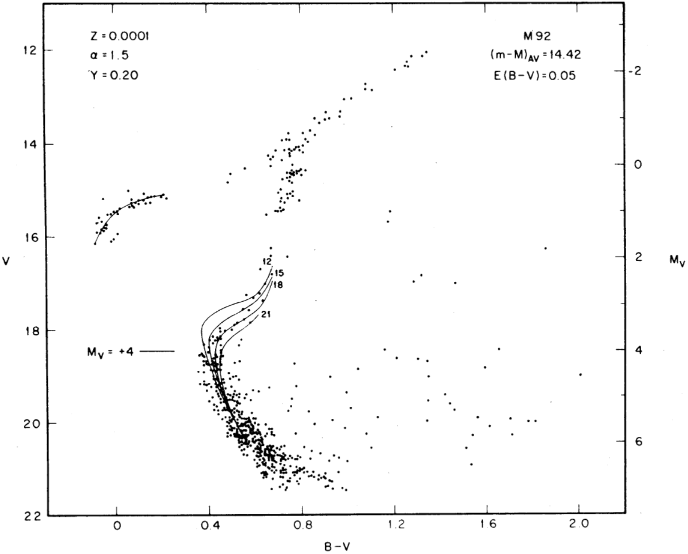
Why has β been so difficult to measure past 15 kpc?

- poor statistics due to small sample sizes
- lack of measurements of tangential velocity dispersion



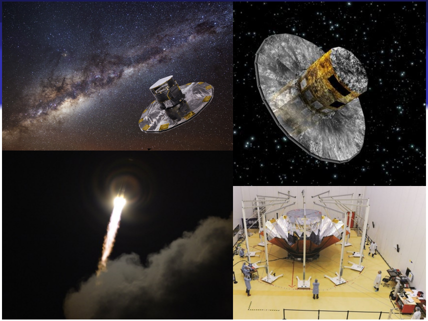
Useful tracers of halo star kinematics Figure: Sandage83

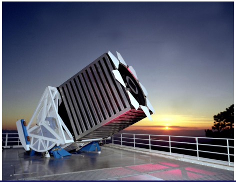
- giant stars
- RR Lyrae
- blue horizontal branch stars



Surveys

- this study:
    - SDSS/SEGUE
    - LAMOST
    - *Gaia*
- more surveys: Subaru HSC and PFS, SDSS-V, GALAH, RAVE, Gaia-ESO, SkyMapper, DESI, WEAVE, HALO7D
- future surveys/ telescopes: WFIRST, Rubin-LSST, JWST, E-ELT, GMT, TMT

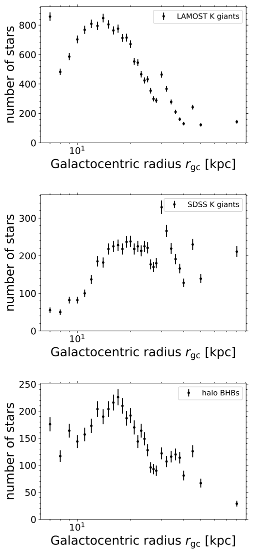




Galactic halo sample

Selection criteria:

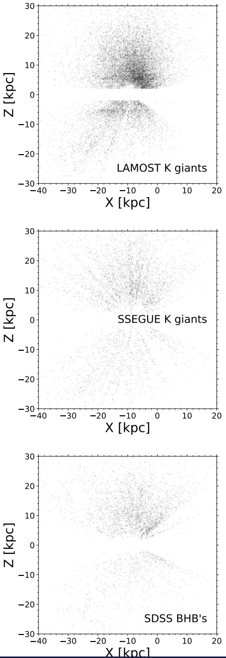
- SDSS/SEGUE+LAMOST DR5+*Gaia* DR2
- K giants
  - LAMOST: defined by $T_{\rm eff}$ and $\log g$ Liu+14
  - SDSS/SEGUE: defined as in Xue+14
  - spectroscopic distances Xue+14
- Blue horizontal branch (BHB) Xue+08
  - limits in color and Balmer line profile
  - photometric distances
- LAMOST K giants: top
- SEGUE K giants: middle
- SDSS BHB: lower



Galactic halo sample

Selection criteria:

- $|Z| > 2$ kpc & $[\mathrm{Fe/H}] < -1$
- (V_r, V_θ, V_ϕ):
  - $V < 500$ km s^{-1}
  - $\delta V < 150$ km s^{-1}
- SDSS/SEGUE:
  - $>$5300 K giants
  - $>$3900 BHBs
- LAMOST DR5: $>$13,000 K giants



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- LAMOST K giants: top
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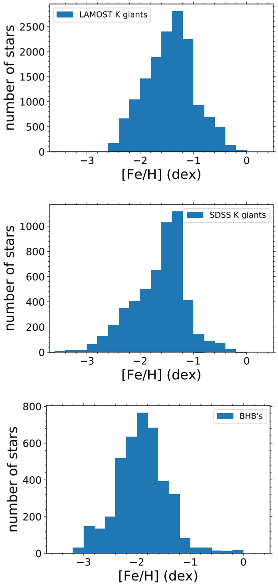
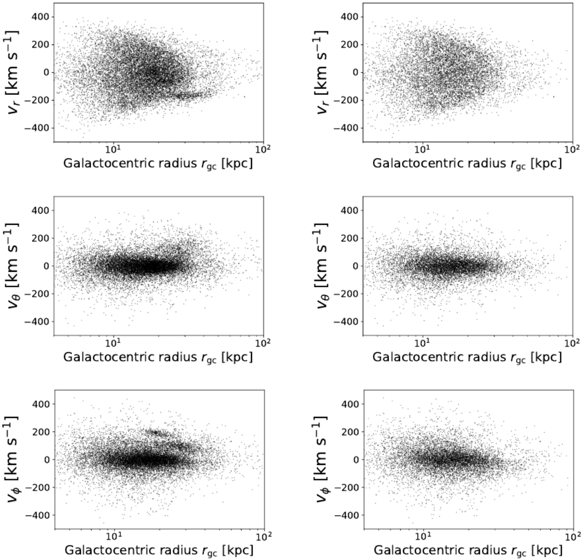


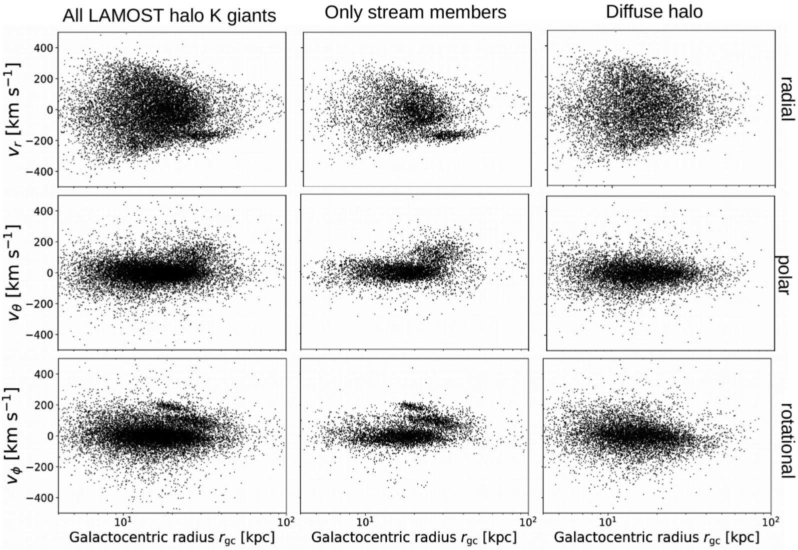
Substructure removal Xue+in prep.

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

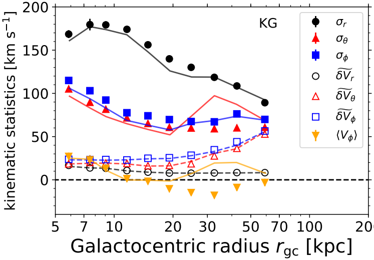


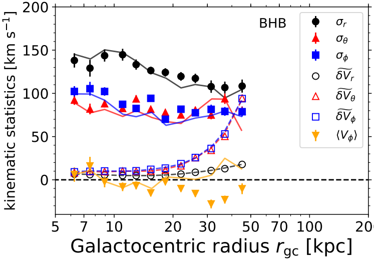
Substructure removal Xue+in prep.



Kinematic statistics vs $r_{\rm gc}$

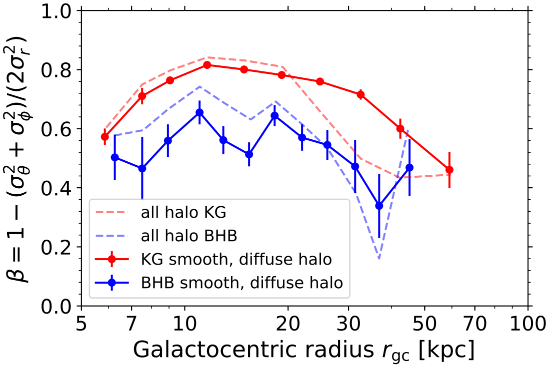
- $\sigma_r > \sigma_\theta, \sigma_\phi$ at all $r_{\rm gc}$
- 3D velocity dispersion profiles dropping for $r_{\rm gc} < 20$ kpc
- evidence of Sagittarius stream $r_{\rm gc} > 20$ kpc
- median velocity uncertainty $\widetilde{\delta V_r}, \widetilde{\delta V_\theta}, \widetilde{\delta V_\phi}$: open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





Velocity anisotropy β

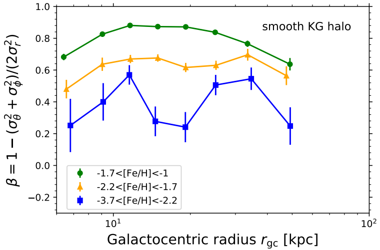
- highly radial within $r_{\rm gc} < 30$ kpc
- gently falls to lower radial values for $r_{\rm gc} > 30$ kpc
- LAMOST/SDSS K giants: red
- SDSS BHB stars: blue
- each marker represents the median distance of binned stars

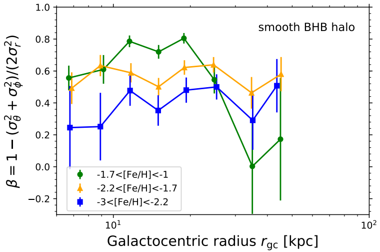


Velocity anisotropy and [Fe/H]

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

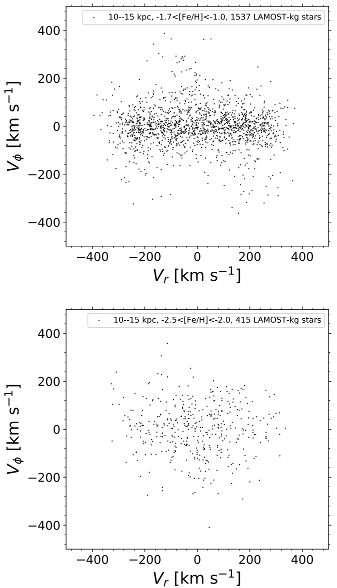
- similar β profile
- similar β dependency on metallicity
- distance and metallicity determinations are in concordance





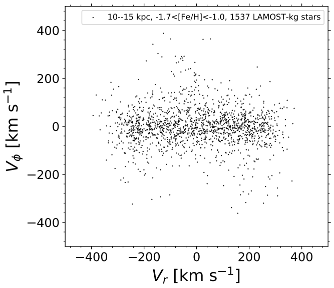
Stellar halo chemodynamics

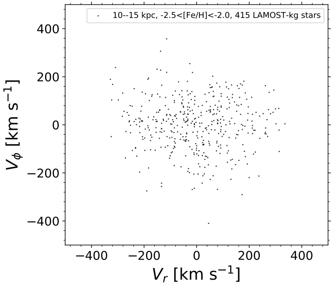
- V_r and V_ϕ distribution at 10 – 15 kpc
- *Upper*: more metal rich and highly radial
- *Lower*: more metal poor and less radial
- Simulations best reproduce such observations after a large ($\sim 10^{11}$ $M_\odot$) satalite merging early on ($\sim$ 10 Gyr ago) e.g. Brook+03, Belokurov+18, Fattahi+19



Chemodynamics

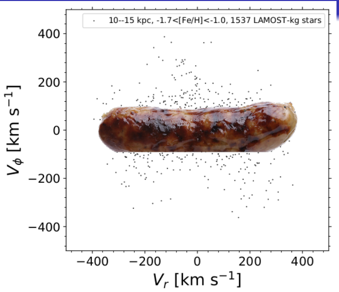
- V_r and V_ϕ distribution
- $10 - 15$ kpc
- *Upper*: more metal rich and highly radial
- *Lower*: more metal poor and less radial
- What do you see?

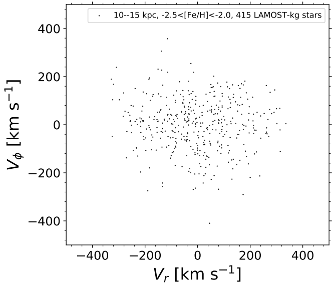




Gaia-Sausage!

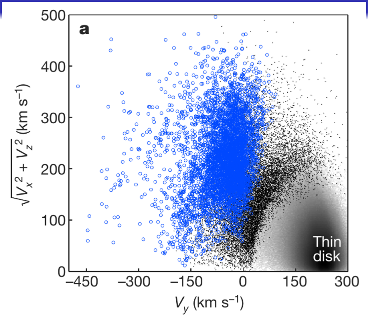
- evidence for a past merged satellite!!!
- V_r and V_ϕ distribution
- $10 - 15$ kpc
- *Upper*: more metal rich and highly radial
- *Lower*: more metal poor and less radial
- Belokurov+18, Deason+18, Myeong+18





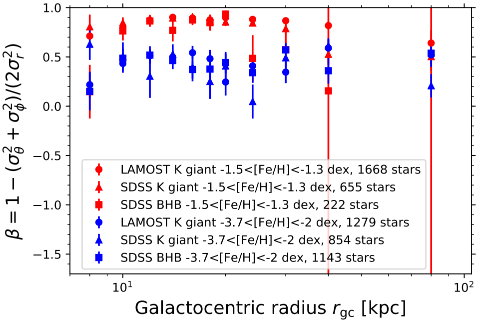
Last significant merger

- blob (Toomre diagram)
- *Gaia*-Enceladus (Greek mythology: a past giant now buried under a mountain)
- Kraken (Scandinavian folklore: elusive, giant, squid-like monster of the sea)
- Koppelman+18, Helmi+18, Kruijssen+18



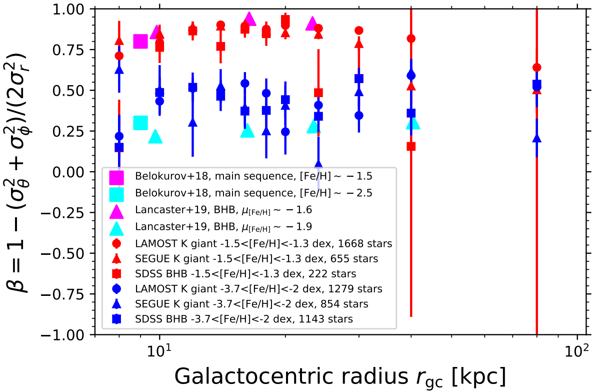
Velocity anisotropy β and chemical abundances

- chemo-dynamically different stellar halo components
- newly discovered in combination with *Gaia* data
- results of merging satellite(s) (e.g. Gaia-Sausage, Sequoia, Gaia-Enceladus, Kraken, blob)
- see, e.g., Belokurov+18, Myeong+18abcd,19, Deason+18, Koppelman+18, Helmi+18, Mackereth+18, Kruijssen+18, Lancaster+19, Simion+19, Bird+19, Vasiliev19, Matsuno+19



Velocity anisotropy β and metallicity Previous Works

- observations: e.g.
  Chiba&Beers2000,
  Carollo+07,
  Carollo+10,
  Hattori+13,
  Kafle+13,17,
  Belokurov+18,
  Lancaster+19
- simulations: e.g.
  Brook+03,
  Amorisco+17,19
  Loebman+18,
  Fattahi+19



3D spherical Jeans equation

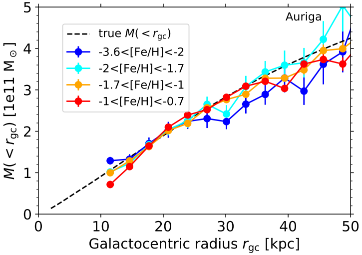
- Equipped with high quality 3D velocity dispersion profiles, we can use the more full 3D spherical Jeans equation and bypass estimating or making assumptions about velocity anisotropy β:

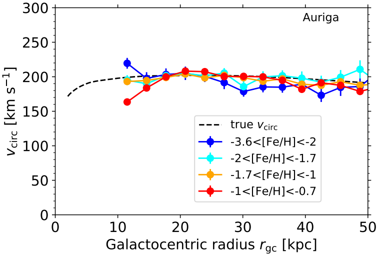
$$M(< r) = -\frac{1}{G}(r^2\frac{d\sigma_r^2}{dr} + r(\sigma_r^2(2+\alpha) - \sigma_\theta^2 - \sigma_\phi^2))$$

  - $(\sigma_r, \sigma_\theta, \sigma_\phi)$ velocity dispersion in spherical coordinates (radial, polar, azimuthal)
  - α power law assuming space density of particles $\propto r^{-\alpha}$
  - assumes a virialized system

Test Jeans with simulations

- 3D spherical Jeans enclosed mass estimate for Auriga Milky Way-type stellar halos Grand+17
- different metallicities with different kinematics and density
- 3D spherical Jeans mass estimate recovers the true mass profile
- before removing substructure
- departure from a virialized and spherical halo is small enough to allow successful use of the 3D spherical Jeans equation

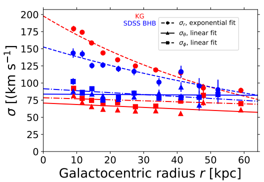


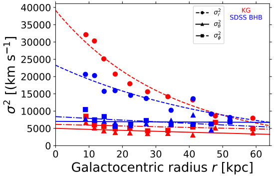


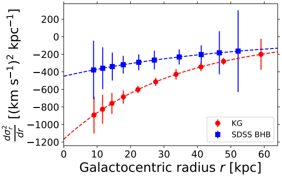
Galactic halo sample

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

- velocity components of Jeans equation for K giants and BHB stars
- data (markers), lines (fits)
- σ_r exponential fit (upper)
- σ_θ, σ_ϕ linear fits (upper)
- σ^2 (middle)
- $\frac{d\sigma_r^2}{dr}$ (lower)
- broken power law density profiles adapted from literature Xue+15,Das & Binney 16, Ablimit+20
    - KG: $\alpha_{\rm in,out} = -3, -3.8$, $r_{\rm break} = 16$ kpc
    - BHB: $\alpha_{\rm in,out} = -3.5, -4.8$, $r_{\rm break} = 20$ kpc

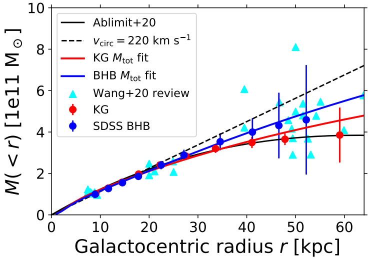


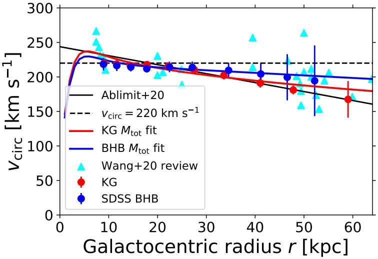




Mass and circular velocity curves

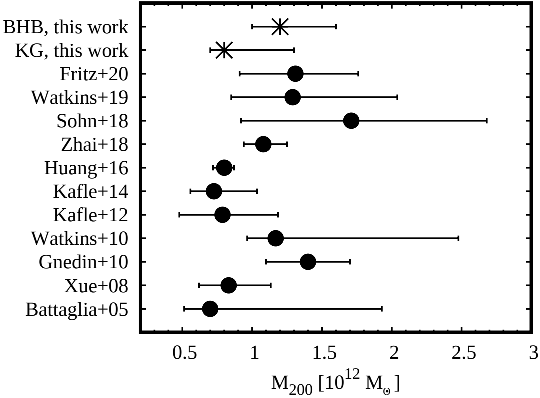
- 3D spherical Jeans mass and $v_{\rm circ}$ for KG and BHB (red and blue markers)
- mass estimates from literature (cyan triangles, summarized in Wang+20)
- $v_{\rm circ}$ of 220 km s^{-1} and Ablimit+20 (dotted and solid lines)
- best fit NFW profile dark matter mass
  - KG $M_{200} = 0.8^{+0.5}_{-0.1} \times 10^{12}$ $M_\odot$ (fitting error)
  - BHB $M_{200} = 1.2^{+0.4}_{-0.2} \times 10^{12}$ $M_\odot$ (fitting error)





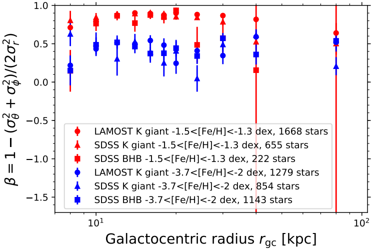
Virial mass comparison

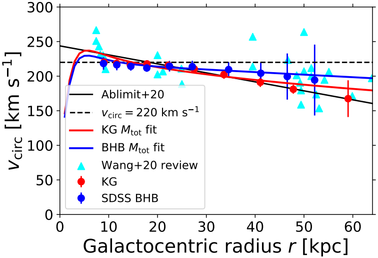
- good agreement
- virial mass M_{200} estimtes using similar methods involving tracer samples
- average mass is $\sim 1 \times 10^{12}$ $M_\odot$ with a scatter of $\sim 30\%$.
- see Wang+20,15 for summary of mass estimates



Key Conclusions and Discoveries

- LAMOST/SDSS + *Gaia* DR2 yield over 22000 halo K-giant and BHB stars
- first presentation of **3D velocity profiles** for such a large and far-reaching halo star sample!
- β **profile** is constant up to distances exceeding $r_{\rm gc} = 20$ kpc
- K giants and BHB's both share similar:
  - **radially dominated** stellar orbits
  - β **dependence on [Fe/H]**
- 3D spherical Jeans mass profile best fit with $M_{200} \sim 1 \times 10^{12}$ $M_\odot$





Next steps

- compare observations to galaxies formed in cosmological simulations
- why do K giants and BHB stars show different velocity anisotropy β?
- quantify the uncertainty introduced by combining the stars types vs separating them
- compare different methods for mass estimation

Thanks!!!

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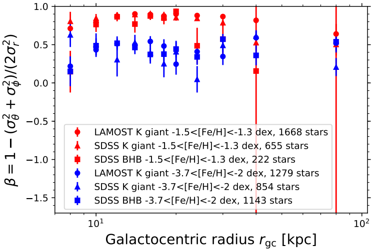

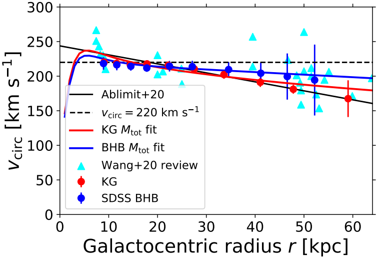

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Publications during Aliyun Fellowship

- **Bird, Sarah A.**; Xue, Xiang-Xiang; Liu, Chao; Shen, Juntai; Flynn, Chris; & Yang, Chengqun; 2019, AJ, 157, 104
- **Bird, Sarah A.**; Xue, Xiang-Xiang; Liu, Chao; Shen, Juntai; Flynn, Chris; Yang, Chengqun; Zhao, Gang; Tian, Haijun; 2020, arXiv:2005.05980, under review for ApJ
- **Bird, Sarah A.**; Xue, Xiang-Xiang; Liu, Chao; Shen, Juntai; Flynn, Chris; Yang, Chengqun; Wang, Jie; Zhai, Meng; Zhu, Kai; Zhu, Ling; Zhao, Gang; & Tian, Haijun; in preparation for ApJ
- Ablimit, Iminhaji; Zhao, Gang; Flynn, Chris; **Bird, Sarah A.**; 2020, ApJ, 895, L12
- Ye, Xianhao; Zhao, Jingkun; Liu, Jiaming; **Bird, Sarah A.**; Liu, Chao; Liang, Xilong; Zhang, Jiajun; Zhao, Gang; 2021, AJ, 161, 8
- Erkal, Denis; Deason, Alis J.; Belokurov, Vasily; Xue, Xiang-Xiang; Koposov, Sergey E.; **Bird, Sarah A.**; Liu, Chao; Simion, Iulia T.; Yang, Chengqun; Zhang, Lan; Zhao, Gang; 2020, arXiv:2010.13789, under review for MNRAS
- Shen, Yu-Fu; Zhao, Gang; **Bird, Sarah A.**, under review for ApJ
- Wu, Wenbo; Zhao, Gang; Xue, Xiang-Xiang; **Bird, Sarah A.**; Yang, Chengqun; in preparation for ApJ
- Liu, Gao-Chao; Huang, Yang; Tian, Haijun; **Bird, Sarah A.**; in preparation for ApJ