Milky Way’s Anisotropy Profile with LAMOST/SDSS and Gaia

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Contents

1 Stellar Halo

2 LAMOST + SDSS + Gaia Halo Stars

3 Results

4 Conclusion
Velocity anisotropy $\beta$ 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
- galaxy formation
  - orbits have long dynamical time scales
  - collisionless system
  - orbital shapes are relatively immune to adiabatic change of the gravitational potential
Mass uncertain by 20% due to uncertainties in $\beta$ alone

- halo K giants
  - $>4100$ SDSS/SEGUE
  - $>6900$ LAMOST DR3

- assume $\beta = 0$, $M_{200} = 0.9 \pm 0.3 \times 10^{12} M_\odot$

- assume $\beta = 0.5$, $M_{200} = 0.7 \pm 0.3 \times 10^{12} M_\odot$
Velocity anisotropy $\beta$ profile

$\beta$ profile as seen by

- Simulations: slowly rising radially
- Solar neighborhood: $\beta > 0.5$
- Observations past 15 kpc: variety of differing results!!!

Why is $\beta$ profile so difficult to measure past 15 kpc?

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

What is the solution?
Stellar Halo

2 LAMOST + SDSS + Gaia Halo Stars

3 Results

4 Conclusion
Galactic halo stars from LAMOST+SDSS+Gaia

Selection criteria:

- SDSS/SEGUE+LAMOST DR5+Gaia DR2
- K giants
  - defined by $T_{\text{eff}}$ and $\log g$ \cite{Liu14}
  - photometric distances \cite{Xue14}
- Blue horizontal branch (BHB) \cite{Xue08}
  - Limits in color and Balmer line profile
  - photometric distances
- $|Z| > 5$ kpc
- $[\text{Fe/H}] < -1.3$ dex
- SDSS/SEGUE
  - $>4100$ K giants
  - $>3700$ BHBs
- LAMOST DR5: $>8600$ K giants
1. Stellar Halo
2. LAMOST + SDSS + Gaia Halo Stars
3. Results
4. Conclusion
Number histogram of LAMOST DR5 halo K giants

Galactocentric radius $r_{gc}$ [kpc]

Number of stars

Milky Way Stellar Halo

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Propagate observational errors to 3D velocities
- line-of-sight velocity
- distance
- proper motions in ra and dec

Monte Carlo sampling to estimate 3D median velocity errors
Velocity, metallicity, $r_{gc}$ Figure: Bird+18 subm.

- evidence of velocity dependency on [Fe/H]
- signs of substructure
Velocity dispersion vs $r_{gc}$ Figure: Bird+18 subm.

- $\sigma_r > \sigma_\theta, \sigma_\phi$ at all $r_{gc}$
- 3D velocity dispersion profiles dropping for $r_{gc} < 20$ kpc
- evidence of Sagittarius stream $r_{gc} > 20$ kpc
Anisotropy vs $r_{gc}$  

- Highly radial within $r_{gc} < 20$ kpc
- Gently falls to lower radial values for $r_{gc} > 20$ kpc
Remove Sagittarius Figure: Bird+18 subm.

- Energy $E$ vs total angular momentum $L$
- Define a Milky Way potential using the python package galpy Bovy 2015
- Select one substructure to remove and see effect on velocity anisotropy
After removal of Sagittarius stream:

- highly radial profile extends further to $r_{gc} < 30$ kpc
- gently falling section is smoothed of jagged features
Anisotropy and [Fe/H] dependency

- the most metal poor K giants
  - less radial orbits
  - constant $\beta$ profile extending to $r_{gc} > 25$ kpc
- $\beta$ can be used to locate substructure see e.g. Loebman+18

\[
\beta = 1 - \frac{\sigma_\phi^2}{(2\sigma_r^2)}
\]

Galactocentric radius $r_{gc}$ [kpc]

$\beta$ versus Galactocentric radius $r_{gc}$ for different [Fe/H] values:
- $-1.5 \leq [\text{Fe/H}] < -1.3$
- $-1.8 \leq [\text{Fe/H}] < -1.5$
- $-2.5 < [\text{Fe/H}] < -1.8$
Anisotropy for LAMOST K giants and SDSS BHBs

\( \beta \) for LAMOST K giants compared with SDSS BHB’s in common metallicity bins:

- similar \( \beta \) profile
- similar \( \beta \) dependency on metallicity
- distance and metallicity determinations are in concordance

\[ \beta = 1 - \frac{(\sigma_\theta^2 + \sigma_\phi^2)}{2\sigma_r^2} \]

<table>
<thead>
<tr>
<th>Metallicity Range</th>
<th>LAMOST K Giants</th>
<th>SDSS BHBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-1.5 \leq [Fe/H] &lt; -1.3)</td>
<td>K giants</td>
<td>BHBs</td>
</tr>
<tr>
<td>(-2.5 \leq [Fe/H] &lt; -1.8)</td>
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</tbody>
</table>
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Key Conclusions and Discoveries

- LAMOST/SDSS + Gaia DR2 yield over 16000 halo K-giant and BHB stars
- Furthest stars exceed 100 kpc
- **First presentation of 3D velocity profiles for such a large and far-reaching halo star sample!**
- 3D velocity dispersion varies with radius
- \( \beta > 0 \): **radially dominated halo star orbits**
- \( \beta \) profile is constant up to distances exceeding \( r_{gc} = 20 \) kpc
- Removing Sagittarius causes \( \beta \) to remain flattened nearly to 30 kpc
- \( \beta \) dependence on \([Fe/H]\): systematic decrease of \( \beta \) for \([Fe/H] < -1.8\)
- K giants and BHB’s both share similar:
  - radially dominated stellar orbits for \( r_{gc} < 30 \) kpc
  - \( \beta \) dependence on \([Fe/H]\)
Next steps

- Compare observations to galaxies formed in cosmological simulations
- Check the influence of removing substructure for SDSS halo samples
- Integrate orbits for our sample
- Use Jeans equation to measure Galactic mass

Thanks!!!
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End of Presentation

Backup Slides
K giants are good distance indicators

halo K-giant photometric distances (from LAMOST/SDSS) largely have smaller errors than Gaia parallax distances
Anisotropy for SDSS/LAMOST K giants and BHBs

\( \beta \) for SDSS BHB’s and K Giants compared with LAMOST K Giants

- \( \beta \) profile for LAMOST and SDSS K giants is similar
- \( \beta \) profile for BHB’s is lower than for K giants: Why?
  - BHB’s peak at lower metallicity
  - \( \beta \) depends on metallicity
  - \( \beta \) binned by [Fe/H] is similar

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

\( r_{gc} \) [kpc]