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The pairwise velocity difference of over 2000 BHB stars in the Milky Way halo *

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Abstract Models of hierarchical galaxy formation predict that the extended stellar halos of galaxies like our Milky Way show a great deal of sub-structure, arising from disrupted satellites. Spatial sub-structure is directly observed, and has been quantified, in the Milky Way's stellar halo. Phase-space conservation implies that there should be sub-structure in position-velocity space. Here, we aim to quantify such position-velocity sub-structure, using a state-of-the art data set having over 2000 blue horizontal branch (BHB) stars with photometry and spectroscopy from SDSS. For stars in dynamically cold streams ("young" streams), we expect that pairs of objects that are physically close also have similar velocities. Therefore, we apply the well-established "pairwise velocity difference" (PVD) statistic $\langle|\Delta V_{\rm los}|\rangle(\Delta \boldsymbol{r})$, where we expect $\langle|\Delta V_{\rm los}|\rangle$ to drop for small separations $\Delta \boldsymbol{r}$. We calculate the PVD for the SDSS BHB sample and find $\langle|\Delta V_{\rm los}|\rangle(\Delta \boldsymbol{r}) \approx$ const., i.e. no such signal. By making mock-observations of the simulations by Bullock & Johnston and applying the same statistic, we show that for individual, dynamically young streams, or assemblages of such streams, $\langle|\Delta V_{\rm los}|\rangle$ drops for small distance separations $\Delta \boldsymbol{r}$, as qualitatively expected. However, for a realistic complete set of halo streams, the pair-wise velocity difference shows no signal, as the simulated halos are dominated by "dynamically old" phase-mixed streams. Our findings imply that the sparse sampling and the sample sizes in SDSS DR6 are still insufficient to use the position-velocity sub-structure for a stringent quantitative data-model comparison. Therefore, alternate statistics must be explored and much more densely sampled surveys, dedicated to the structure of the Milky Way, such as LAMOST, are needed.

Key words: cosmology: dark matter — galaxies: individual (Milky Way) — galaxy: halo — stars: horizontal-branch — stars: kinematics

1 INTRODUCTION

The current paradigm of hierarchical structure formation predicts that our Milky Way was formed in a sequence of dark matter driven accretion and merger events (White & Rees 1978; Searle & Zinn 1978; Blumenthal et al. 1984; Bullock & Johnston 2005, hereafter BJ05). This naturally results in the

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expectation that the stellar halo should be largely built up from disrupted satellites, resulting in sub-structures that may appear as stellar streams. Therefore, the distribution of stars in the halo is of great importance to test such models of galaxy formation. Because stars act like collisionless systems, their spatial and velocity distributions can be used to trace their dynamic origin.

In the past decades, observational evidence for such sub-structures has indeed been found in the Milky Way, both near the Sun (Majewski et al. 1996; Helmi et al. 1999) and at larger distances (Ibata et al. 1994, 1995). The most prominent example is the discovery of the Sagittarius dwarf galaxy (Ibata et al. 1994, 1995) and its trails of debris (Majewski et al. 2003; Ibata et al. 2001b). The advent of large-scale sky surveys, such as the Two Micron All Sky Survey (2MASS), the Sloan Digital Sky Survey (SDSS) and the follow-up SEGUE survey (Abazajian et al. 2009; Yanny et al. 2009), provided an unprecedented opportunity to look at Milky Way halo streams in detail (Majewski et al. 2003; Ivezić et al. 2000; Yanny et al. 2000; Newberg et al. 2002; Yanny et al. 2003; Newberg et al. 2007; Yanny et al. 2009). The data have now become good enough that a direct statistical comparison with models, such as BJ05, has become possible. A first quantitative comparison (Bell et al. 2008, hereafter B08) indicates that the observed level of *spatial* sub-structure (on all scales) is similar to that expected from those simulations, where the entire halo is composed of disrupted satellites. Imaging surveys of M31 (Ibata et al. 2007) have revealed a similarly rich set of sub-structures in the stellar halo of that galaxy.

Because the stellar halo is a collisionless system which preserves phase space density, sub-structure in position space necessarily implies sub-structure in velocity space. Indeed, in nearby samples of stars, where all 6D phase space coordinates can be measured, sub-structure in the stellar distribution is seen in velocity space, or even the space of integrals of motion (Dehnen & Binney 1998; Helmi et al. 1999; Klement et al. 2008, 2009). At distances from the Sun characteristic of the stellar halo, $\sim$20 kpc, individual transverse velocities are all but impossible to measure from proper motions with current technology. The observables are therefore the position in the sky, a distance estimate from photometric or spectroscopic luminosity determinations, and line-of-sight velocity.

Based on the photometry of main sequence turn-off (MSTO) stars, B08 constructed a coarse 3D map of the stellar halo density, with almost a factor of 2 uncertainty in distances. BHB stars are a much rarer tracer of the old metal poor population, but have the great advantages of being luminous $M_g \sim +0.7$ (vs. $M_g \sim 3.5$ for MSTO stars) and that their distances can be estimated to $\sim 5\%$ (Xue et al. 2008, hereafter X08).

BHB stars lend themselves to sparse halo maps with greater radial resolution (e.g. Newberg et al. 2003; Bell et al. 2009). BHB stars have also been a special spectroscopic target class in SDSS and SEGUE (e.g. Yanny et al. 2009). Hence, the BHB sample with spectra from SDSS constitutes by far the largest set of luminous tracers (to ~ 60 kpc) of the Milky Way's stellar halo with four dimensional $(\alpha, \delta, D, V_{\rm los})$ information, good distances (accurate to 5%) and radial velocities (errors are between 5 and 20 km $\rm s^{-1}$).

In this paper, we present an initial exploration of how to quantify position-velocity sub-structure in the Milky Way's stellar halo, comparing the observation to the levels expected from simulations, such as BJ05. It is possible to pick out velocity sub-structures, such as the Sagittarius stream (e.g. Ibata et al. 2001b). What we aim for here is to devise a simple objective measure for quantifying any such sub-structure. To constrain the radial mass profile of the Milky Way's halo, we have identified a sample of halo blue horizontal-branch (BHB) stars from SDSS DR6 (X08). That sample comprises 2401 rigorously selected BHB halo stars ($\lesssim 10\%$ contamination) at $|z| \geq 4$ kpc, and with distances from the Galactic center up to ~ 60 kpc; they have distances accurate to $\sim 5\%$ and radial velocities with errors between 5 and 20 km $\rm s^{-1}$. To take out the effects of globular clusters on the detection of sub-structure, we eliminate 9 stars belonging to globular clusters. Based on the 2392 BHB stars, in the present paper, we devise a statistic called the pairwise velocity difference (PVD) aimed at quantifying sub-structure in the stellar halo. As also argued by B08, it is important for quantitative data-model comparison to have a general statistical measure of sub-structure, rather than specifically searching for (here, kinematical) sub-structure associated with a particular feature, such as the Sagittarius stream.

We organize our paper as follows. In Section 2, we will give a general overview of our BHB sample. In Section 3, we describe the definition of the pairwise velocity difference and the result of applying it to the BHB stars. Bullock & Johnston's cosmological simulations are presented in Section 4. That section also describes the statistical analysis of the simulations. In Section 5, we present the conclusion obtained from the comparison between observations and simulations.

2 DATA: THE BHB SAMPLE FROM DR6

We use the BHB sample of 2392 stars rigorously selected from SDSS DR6 and presented in X08. For details of the procedure of sample selection, we refer the interested reader to X08. Here we just give a general overview of the sample's properties. Figure 1 shows the angular and spatial distribution and line-of-sight velocity distribution of the BHB sample. The line-of-sight velocities, $V_{\rm los}$, are converted from the Local Standard of Rest frame to the Galactic Standard of Rest frame by adopting a value of 220 km s^{-1} for the Local Standard of Rest ($V_{\rm lsr}$) and a Solar motion of $(+10.0, +5.2, +7.2)$ km s^{-1} (as in X08). The spatial coordinate system, (x, y, z), is defined in a right-handed Galactic system with x pointing towards the Sun, y being the direction of rotation, and z towards the north Galactic pole. This sample of halo BHB stars has well-estimated radial velocities (errors between 5$\sim$20 km s^{-1}) and more accurate distances than other halo stars (i.e. MSTO). This sample, therefore, has four times more accurate distances and 15 times more data points than the sample of halo giants recently used by Starkenburg et al. (2009) in a search for distant kinematic halo sub-structure.

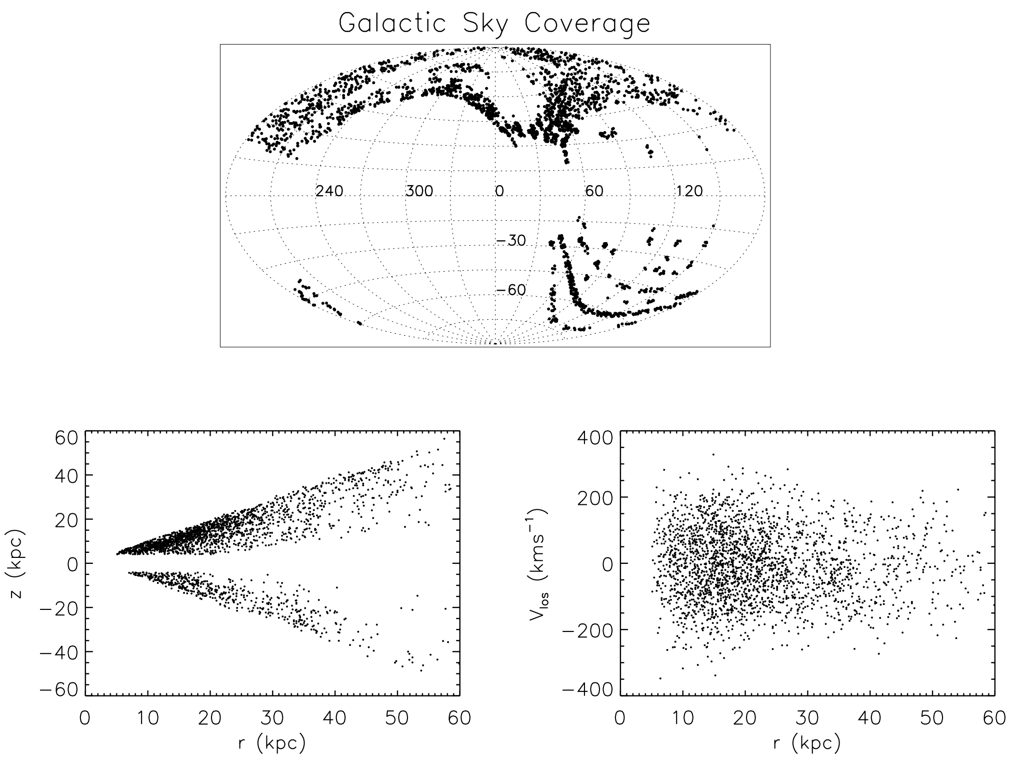

Fig. 1 *Top panel* shows the sky coverage of the BHB sample in SDSS DR6 analyzed here. The *bottom left panel* shows the spatial distribution of the BHB stars in the r-z plane. The *bottom right panel* shows the line-of-sight velocity distribution of the BHB sample, which reveals no obvious distance-velocity sub-structure.

3 QUANTIFYING POSITION-VELOCITY SUB-STRUCTURE IN THE BHB STARS

In this section, we introduce a simple statistic, the "pairwise velocity difference," designed to detect and quantify sub-structure. Note that the goal is not primarily to find any particular structure, which may be best done "by eye," but to devise a statistical measure to quantify and compare it. While it is clear that sub-structure in phase-space, as may arise from the tidal disruption of satellite galaxies, must leave some signature in position velocity space, it is not clear *a priori* what statistic to use to quantify it, or search for it. One approach could be to transform the observables [here: equatorial coordinate (α, δ); distance to the Sun d; line-of-sight velocity $V_{\rm los}$] to more suitable coordinates, such as the space of the integrals of motion or action-angle variables (e.g. Helmi et al. 1999; Klement et al. 2008, 2009). This entails a number of complications, such as appropriate priors for the unobserved (unobservable) coordinates and prior assumptions about the gravitational potential. Here, we explore the conceptually and practically simplest approach, the search for position-velocity correlations in the directly observable coordinates.

This statistic, the pairwise velocity difference (PVD), is very similar to the well-established "pairwise velocity dispersion," which has been successfully applied to characterizing the position-velocity correlations in galaxy surveys (Jenkins et al. 1998; Zehavi et al. 2002; Efstathiou & Eastwood 1981).

If stellar halos were well described by a power-law density distribution and a local velocity dispersion ellipsoid, it is clear that basically no position-velocity correlation among the stars would be expected, as the line-of-sight velocity dispersion is nearly independent of distance at 111 km s $^{-1}$ (X08). In contrast, the simple case of a dynamically cold stream of stars that is spread out, say, $\leq 2\pi$ in phase, may serve as a qualitative guide to what we expect *statistically* in the presence of sub-structure. In that case, pairs of stars that are particularly close in 3D positions, i.e. small $\Delta \boldsymbol{r}$, should have very similar line-of-sight velocities, $\Delta V_{\rm los}$.

Qualitatively, pairs of stars close in 2D angular positions should show similar $V_{\rm los}$, but the 3D information for BHB stars allows us to greatly reduce projection contamination.

Based on this qualitative picture, we explore the probability distribution P($|\Delta V_{\rm los}|, \Delta \boldsymbol{r}$) for pairs of stars in both our BHB sample and in mock-observations of BJ05 simulations. Specifically, we look at the 1st moment (in $\Delta V_{\rm los}$) of this distribution,$\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta \boldsymbol{r})$, in particular compared to the "null hypothesis," where $|\Delta V_{\rm los}|$ and $\Delta \boldsymbol{r}$ are uncorrelated.

We start by displaying the full P($|\Delta V_{{\rm los},ij}|, \Delta \boldsymbol{r}_{ij}$) distribution for the sample of BHB stars in Section 2. With a sample of 2392 stars, we can form $\sim 2.8 \times 10^6$ pairs $|\Delta V_{{\rm los},ij}|$ and $\Delta \boldsymbol{r}_{ij}$. In Figure 2, we show the two-dimensional distribution N($|\Delta V_{\rm los}|, \Delta \boldsymbol{r}$) normalized by N($\Delta \boldsymbol{r}$) on a relatively fine grid. Figure 2 shows no obvious shift towards small $|\Delta V_{\rm los}|$ for small $\Delta \boldsymbol{r}$. Figure 2 also shows no excess in the tails of the distribution at small velocity differences for small spatial separations. This figure suggests that an even simpler statistic, such as the PVD, is sensible.

Note that the mean radial velocity errors $\delta V_{\rm los}$ are about 7 km s^{-1}, so the corresponding error of $\log_{10}|\Delta V_{\rm los}|$ is about 1.0. The fact that the bulk of $\log_{10}|\Delta V_{\rm los}| \approx 2.2$ at all radial separations is therefore unaffected by $\delta V_{\rm los}$. The typical distance error is 2.0 kpc, so the leftmost bins may be smeared by distance errors. However, as the subsequent figures show (e.g. Fig. 4), a PVD "signal" from cold streams is expected to be seen for $\Delta \boldsymbol{r} < 10$ kpc.

As mentioned, there is no unique choice of a sub-structure statistic, nor is there a rigorous way to derive one without making very specific assumptions about what to expect. Our choice of the pairwise velocity difference as a statistic is therefore only a first step.

The *pairwise velocity difference* (PVD), $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta \boldsymbol{r})$, is defined as the mean line-of-sight velocity difference over all (i,j) in a 3D separation bin; i.e. the mean overall pairs with $\Delta \boldsymbol{r}_{ij} \approx \Delta \boldsymbol{r}$. We define the 3D position difference and line-of-sight velocity difference between two stars i and j as follows:

$$|\Delta V_{{\rm los},ij}| = |V_{{\rm los},i} - V_{{\rm los},j}|\,, \tag{1}$$

$$\Delta \boldsymbol{r}_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}\,, \tag{2}$$

where $V_{{\rm los},i}$ is in the Galactic standard of rest frame (see Sect. 2).

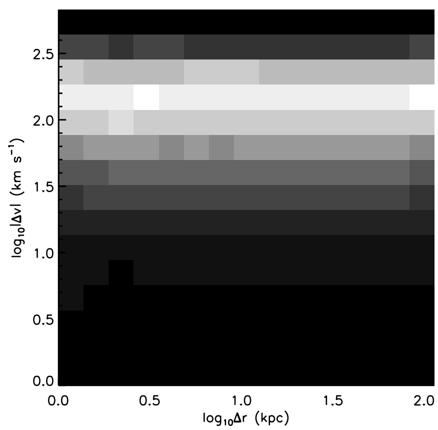

Fig. 2 2D distribution $N(|\Delta V_{\rm los}|, \Delta \boldsymbol{r})$ on a fine grid, normalized by the total number of pairs of stars in each column, $N(\Delta \boldsymbol{r})$. Bright colors indicate more pairs on this plot.

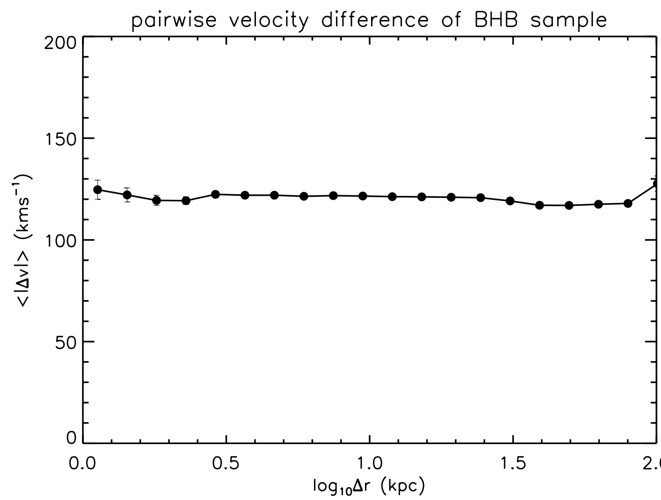

Fig. 3 Pairwise velocity difference as a function of Δr for the BHB sample. The filled circles are the average of $\Delta V_{\rm los}$ for all pairs in different Δr bins, and the error bars reflect bootstrap errors.

As mentioned before (and demonstrated in Sect. 4), we would expect to see some decrease of $\langle|\Delta V_{\rm los}|\rangle(\Delta \boldsymbol{r})$ for small $\Delta \boldsymbol{r}$, if dynamically young (i.e. not fully phase-mixed) streams are prevalent in the stellar halo.

We quantify this observational result in Figure 3, where we show PVD, $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta \boldsymbol{r})$, in a set of radial bins. Figure 3 represents our basic observational results and shows that $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta \boldsymbol{r})$ is nearly constant as a function of position separation $\Delta \boldsymbol{r}$, showing no evidence for any dip at small $\Delta \boldsymbol{r}$, and hence no evidence for prevalent young stellar streams.

Given that we see no evidence for significant position-velocity sub-structure, we explore quantitatively what we should expect from particular models of halo streams (BJ05 simulations) in the next section.

4 POSITION-VELOCITY SUB-STRUCTURE IN THE BJ05 SIMULATIONS

Bullock & Johnston (2005) published models for the formation of the stellar halo of the Milky Way system, arising from the accretion of $\sim 100-200$ luminous satellite galaxies in the past ~ 12 Gyr. They use a hybrid semi-analytic plus N-body approach that distinguished explicitly between the evolution of light and dark matter in accreted satellites. The simulations produce a realistic stellar halo, with a mass and density profile much like that of the Milky Way (e.g. Bell et al 2008), and with surviving satellites matching the observed number counts and structural parameter distributions of the satellite galaxies of the Milky Way.

For further details of the simulations, we refer the interested reader to Bullock & Johnston (2005) and references therein. There are 11 simulated halos provided by Bullock & Johnston. In this section, we will introduce the analysis procedure by one simulated halo named halo15, and then show the PVDs for all 11 simulated halos.

We assume here that BHB stars are representative tracers of the overall population of metal poor, old halo stars (see, however, Bell et al. 2009). We then make "mock observations" within BJ05 simulations, by accounting for the particular survey volume of SDSS, luminosity weight of the simulated particles, and by adding the observational uncertainties for distance and velocity.

From the simulations, we can obtain the particles' 3D positions and 3D velocities in the Galactic standard of rest frame, and luminosities L. We transfer these to galactocentric line-of-sight velocities, $V_{\rm los}$, and sky positions, (l, b), by taking the Sun's position as $(8.0, 0, 0)$ kpc. The probability of a particle being drawn is proportional to the assigned particle luminosity. We also consider the spectroscopic sky coverage of SDSS DR6.

A simulated particle with higher luminosity stands for more "stars" than a faint one, which leads to higher probability of luminous particles being selected. We do this by drawing a fresh random number $a \in (0, 1)$ and accepting the particle only if $a \leq L_*/L_{\rm max}$. To simulate the observations well, an error of 5% is added to distance, while the radial velocities are added with an error of 5$\sim$20 km s^{-1}.

The following analysis is based on the "mock-observations" of 2392 stars in the simulations, which lie in the same sky region as SDSS, have the same distance distribution and velocity uncertainties as the BHB sample, and have distance limits of $|z| \geq 4$ kpc, $6\ \text{kpc} \leq r \leq 60$ kpc, and luminosity weight. This allows us to consider *pairwise velocity difference* for BJ05 simulations.

In the BJ05 simulations, the particles are tagged by stream membership, allowing us to look at the PVD signal of individual streams. Within the simulated halo, there are remains of relatively recently disrupted satellites that still appear as "streams" in the sky (which we dub "dynamically young" streams), and others that are so thoroughly phase mixed that they appear almost uniformly distributed across the sky ("dynamically old" streams). In Figure 4, we show (in the left panel) the sky coverage of a "dynamically young" stream (top) and a "dynamically old" stream (bottom) in the mock-observation of the simulation named halo15. Note that the red dots mimic the SDSS DR6 sky coverage. The corresponding PVDs, $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta \boldsymbol{r})$, are shown and behave as expected: for a "dynamically young" stream, the PVD drops strongly towards small $\Delta \boldsymbol{r}$, exactly the behavior which the PVD was designed to capture. We checked that the superposition of several "dynamically young" streams exhibits the same PVD behavior. In contrast for a dynamically old, phase-mixed stream, the PVD curve either stays flat or even rises for small $\Delta \boldsymbol{r}$ (see bottom right panel of Fig. 4). In this case, physically close pairs often constitute orbit crossings at very different orbital phases and, therefore, at different velocities.

Figure 5 shows the PVD for many streams in the same halo taken individually, along with the total PVD. This figure shows that the majority of streams in a typical halo simulated by BJ05 are dynamically "old" in the sense just described. In light of this, it is then no surprise that the PVD for a mock sample drawn from all simulated streams in one halo shows a nearly flat PVD (thick solid line in Fig. 5). It is important to remember that the entire halo in every BJ05 simulation is made up of disrupted satellites.

The PVDs of mock observations for all 11 simulated halos of BJ05 are shown in Figure 6. Note that Figure 6 shows that, for most simulated halos, the PVDs drop at larger $\Delta \boldsymbol{r}$, but not all simulated halos present this appearance. The total PVDs for some of the BJ05 halos exhibit exactly the $\langle|\Delta V_{\rm los}|\rangle(\Delta \boldsymbol{r}) \approx$ const. behavior seen in our data. From the sky coverage of SDSS DR6 (shown as

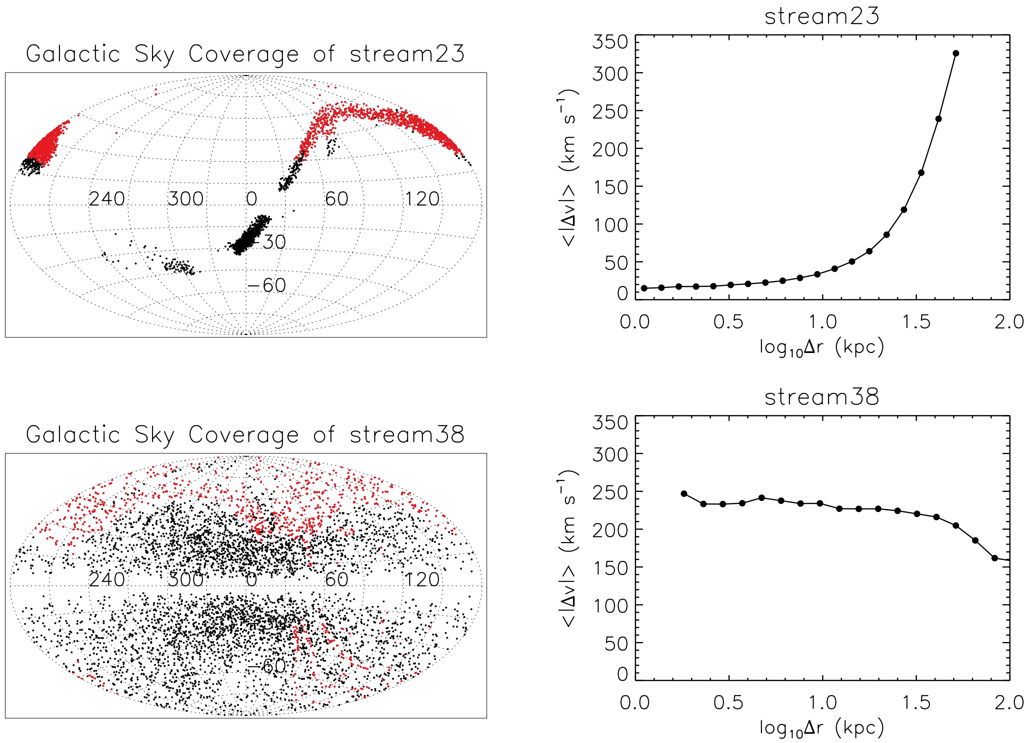

Fig. 4 Examples of young and old streams in a BJ05 simulation named halo15. Only particles that satisfy the selection criteria $|z| > 4$ kpc and $6\,\mathrm{kpc} < r < 60$ kpc are shown. The upper panel is sky coverage and pairwise velocity difference for an example of a young stream in halo15, and the lower panel is for an example of an old stream in the same simulated halo. On the sky coverage plots, the red dots are particles in SDSS volume, while the black dots are full sky particles. The PVDs in the right panel have been calculated from the SDSS sky coverage only (*red dots*).

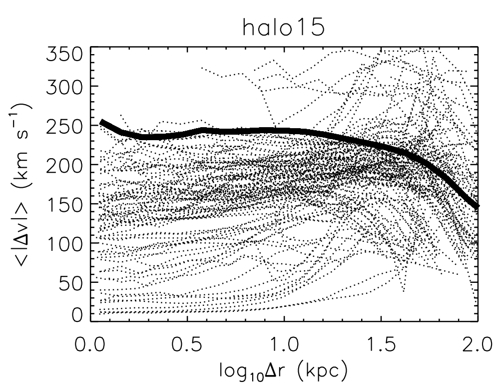

Fig. 5 Pairwise velocity difference of an individual stream and the mix of all streams in the mock observation of halo15. The dotted lines show pairwise velocity difference as a function of Δr for individual streams in the mock observation of halo15, and the thick solid line shows the PVD for the entire mock observation.

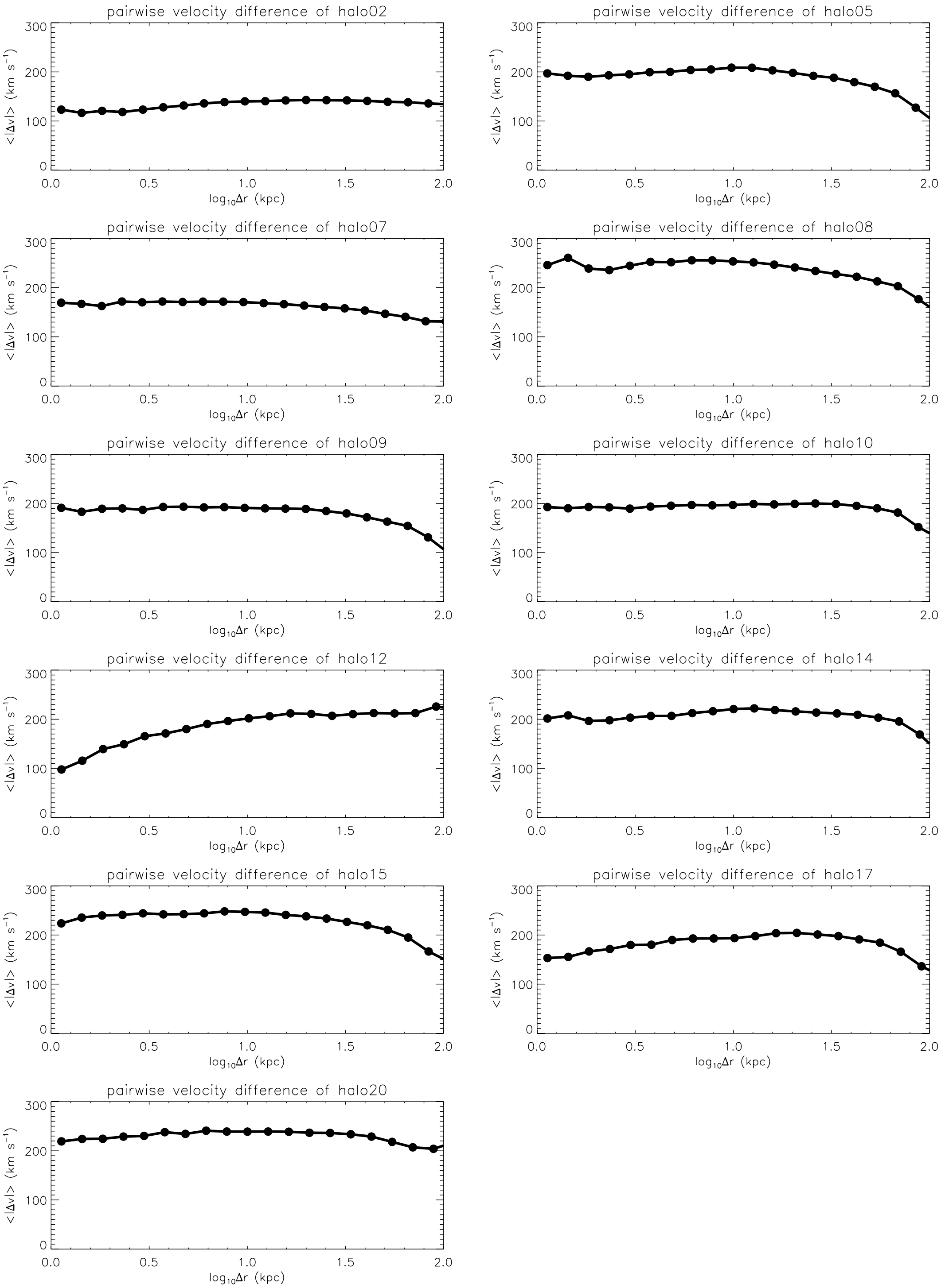

Fig. 6 Pairwise velocity difference of mock-observations for all 11 simulated halos of BJ05. The solid line is the pairwise velocity difference as a function of Δr for the entire mock observation of the corresponding simulated halo, and the filled circles are estimates of $\langle|\Delta V_{\mathrm{los},ij}|\rangle$ at different bins of Δr.

the top panel of Fig. 1), we can conclude that the case of $\Delta\boldsymbol{r} \approx 100$ kpc only occurs for a few pairs in the SDSS survey volume with $r < 60$ kpc, so the PVD at larger $\Delta\boldsymbol{r}$ depends on the particular stream geometry and shows considerable variation.

Overall, however, this comparison implies that the observed PVD, based on the BHB sample, is consistent with the BJ05 simulations. Unfortunately, on the basis of the PVD statistic, the data are also consistent with the null hypothesis of a dynamically "smooth" halo. However, we constructed variations of the BJ05 halos, consisting only of "dynamically young" streams; for such halos, the mock observations for the superposition of the young streams do show a drop in $|\Delta V_{\rm los}|$ at small position separation $\Delta\boldsymbol{r}$, at variance with the actual observations.

5 SUMMARY AND DISCUSSION

In our current cosmogony, the stellar halos of galaxies like our Milky Way are expected to be made up in good part of disrupted satellite galaxies. After disruption, the dispersing stars will form recognizable streams for some time, but may eventually phase-mix beyond easy recognition. There has been recent evidence (B08) that the degree of spatial sub-structure actually seen in the Milky Way's sub-halo matches that of simulations (BJ05) where the stellar halo arises exclusively from disrupted satellites. The same scenario predicts qualitatively a position-velocity correlation.

It is indeed established in the literature that several prominent sub-structures exist in the Milky Way's stellar halo. The next step for that field is to find simple, robust statistical measures to quantify the level of sub-structure to allow direct comparison with theoretical models (such as that of Bullock & Johnston 2005). There is certainly no established way, and no easy way to establish, such a statistic. In purely position space, the state-of-the art is to simply take the rms deviation of the density from a power-law model (Bell et al. 2008); rms is an extremely simple statistic, but one to try first. By analogy in this paper, we explore the utility of perhaps the simplest, and certainly one of the most well established, statistics for looking for position-velocity correlations: the pairwise velocity difference.

In this paper, we present a first practical attempt to objectively quantify such sub-structure of halo (BHB) stars from SDSS. As the specific statistic, we calculate the pairwise velocity difference (PVD) as a function of (3D) distance separation between pairs of stars, $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta\boldsymbol{r})$. Qualitatively, the signal we look for is that the PVD drops at small physical separations, where the probability that two stars come from the same stream (and hence have similar velocities) increases. We show that, for dynamically young streams in the BJ05 simulations, $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta\boldsymbol{r})$ strongly decreases for small $\Delta\boldsymbol{r}$, a signal that we can search for in the data.

Even though the sample of distant halo stars is more than an order of magnitude larger than previous samples of distant halo stars (e.g. Wilhelm et al. 1999; Clewley et al. 2004; Battaglia et al. 2005; Starkenburg et al. 2009) and has more precise distances, we find that the PVDs of the DR6 BHB star sample show no "signal" of position-velocity sub-structure: the observed $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta\boldsymbol{r})$ is very nearly constant as a function of distance separation $\Delta\boldsymbol{r}$. However, our subsequent comparison with BJ05 models showed that this is not inconsistent with a merger origin of the stellar halo. Indeed $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta\boldsymbol{r}) \approx$ const. is consistent with the model of BJ05 because there are enough dynamically old (phase-mixed) streams in the models, which show no drop in $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta\boldsymbol{r})$ as $\Delta\boldsymbol{r}$ nears 0. Their contributions to the overall signal are more significant than the dynamically young streams. If we only consider the dynamically young streams in the BJ05 simulations (see Fig. 5), which are about one-third of the total stellar streams, the total PVD drops towards small separations. Therefore, our newly derived $\langle|\Delta V_{{\rm los},ij}|\rangle(\Delta\boldsymbol{r})$ implies that the Milky Way's stellar halo cannot be dominated by young streams.

While the inability to discriminate the BJ05 models from a smooth halo model on the basis of a simple PVD statistic is somewhat disappointing, the present paper constitutes significant progress in several ways:

(1) It presents the first application of such a simple, plausible and well-established statistic to such a large sample of distant halo stars.
(2) It constitutes the first consistent quantifiable comparison of observed position-velocity data for distant halo stars to the cosmological simulations.

Nonetheless, our results imply that a better "statistic" than the PVD that captures and quantifies the position-velocity sub-structure may be needed. We tried, e.g. the close pair distribution statistic proposed by Starkenburg et al. (2009), to the same data, but also found no "signal" in the data. Beyond mathematics, data improvements may also be needed. There are initial indications that much more densely sampled data than SDSS DR6 (as are now emerging from SEGUE-II) do provide a 'signal'. However, this analysis is still ongoing, and comparison with cosmological models at high resolution is proving difficult as the simulations do not have the resolution to readily provide mock-observations on arcminute scales. Therefore, the present paper only presents a milestone in an ongoing line of research, but we view it an important step.

However, these emergent results, part of an ongoing analysis, are the basis for optimism that a densely sampled survey, such as LAMOST, will provide a powerful diagnostic, as much of the observable "signal" may be on a small scale.

The Large Sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST), in particular the planned Galactic Survey (Zhao et al. 2006), will provide a chance to obtain such a large sample of BHB stars in the future. LAMOST is unique in combining a large aperture (4-meter) with a wide field of view (5-degree) and is equipped with an unprecedentedly large 4000-fiber spectrograph. LAMOST can provide 4000 spectra of objects down to $V\sim 20.5$ with 1 nm spectral resolution in a 1.5-hour exposure, and should be able to target more than 2.5 million halo stars, including more than 20 000 BHB stars.

Such data should revolutionize how we study our own Milky Way, and in this context, reveal the position-velocity sub-structure of the stellar halo, a track record of our Galaxy's accretion history.

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