3. Exploration of the distribution of debris in simulated stellar halos

—Observational strategies and the recovery of building blocks

Abstract

In the coming years, wide-field multi-object spectrographs such as WEAVE and 4MOST will perform massive surveys with the goal of unravelling the dynamics and evolution of the Milky Way. In this chapter provides some guidance specifically on strategies to map the Galactic halo in order to recover merger debris. To this end, we explore the spatial, kinematic and metallicity distributions of debris in cosmological simulations of stellar halos. We quantify the effects of using different tracers such as red giant branch (RGB) or main sequence turn-off (MSTO) stars, and the impact of survey coverage on the sky. We find that RGB stars are the best tracers and that the fraction of building blocks with \( M_\ast > 1.7 \times 10^4 M_\odot \) that can be recovered increases almost linearly with sky coverage. A minimum of 10,000 sq.deg. is necessary to find at least half of the building blocks, and such a survey will reveal significant structure in the kinematics and metallicity distributions. The brighter RGB stars can be used for high resolution studies and in a survey of 5,000 sq.deg. will reveal at least 50% of the building blocks present in the volume probed, and with comparable mass to the classical dwarf spheroidals. Systems comparable to the ultra-faint dwarf galaxies, will mostly be detected using MSTO stars and a targeted follow-up of photometric overdensities ought to be preferred to an unbiased survey covering a large portion of the sky.

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1 Authors: H. Tian & A. Helmi, to be submitted
3.1 Introduction

In the modern cosmological paradigm, galaxies like the Milky Way are believed to have grown in mass via mergers (White & Rees, 1978). The remnants of such mergers events are predicted to be primarily in their halos (stellar and dark matter, see Helmi & White, 1999; Helmi, 2008). Thus by studying the stellar halo of a galaxy we can hope to understand its formation path (Johnston et al., 2008). Because of current limitations of observational techniques, it is quite difficult to observe stellar halos in external galaxies because of their low surface brightness. Furthermore, studies using resolved stars are limited to a few galaxies beyond the Local Group (e.g. Monachesi et al., 2016). In contrast for the Milky Way, we can determine the kinematical and astrophysical properties for a large number of stars, which is critical for galactic archaeology studies (Freeman & Bland-Hawthorn, 2002).

This is in fact a golden age for Galactic archaeology. Large surveys such as SDSS\(^2\) (York et al., 2000) and PanStarrs\(^3\) (Slater et al., 2013; Bernard et al., 2016) have completely changed our view of the outer halo of the Milky Way, revealing a complex mixture of streams and large spatial overdensities thanks to multi-band photometry and large sky coverage (Belokurov et al., 2006b; Bonaca et al., 2012; Bernard et al., 2016). The debris discovered still retains a relatively large degree of spatial coherence, making its detection feasible with photometry only (Newberg & Carlin, 2016; Grillmair & Carlin, 2016). However, photometry is insufficient to detect older debris or debris located in the inner halo, and kinematic information is imperative (Smith, 2016; Gómez et al., 2013). This is because the merger debris is too phase-mixed and its spatial coherence is lost (Helmi & White, 1999).

Launched in December 2013, the Gaia\(^4\) space mission is currently carrying out a census of all the stars brighter than \(G = 20.7\) over a period of 5 years (Perryman et al., 2001; Gaia Collaboration et al., 2016a). From this data accurate proper motions and parallaxes will be obtained for a billion stars in the Milky Way. Gaia will also measure radial velocities for the brighter stars, those with \(G < 16\). Therefore at the end of the mission, Gaia will have obtained tangential velocities for a billion stars but radial velocities only for 15\% of those. This has led the community to push for the development of wide-field high multiplex multi-object spectrographs on 4m and 8m class telescopes. Two examples in the European scene are WEAVE\(^5\) (Dalton et al., 2012) on the WHT in the Canary Islands and 4MOST\(^6\) on the VISTA telescope at ESO (de Jong et al., 2012). Both projects will carry out massive spectroscopic surveys of a representative sample of the stars observed by Gaia with two different modes: a high resolution with \(R = 20,000\) and low resolution mode with \(R = 5,000\). The low resolution mode will allow the measurement of precise radial velocities for stars with magnitudes \(16 < G < 21\) in a reasonable amount of time. From the high resolution mode it will be possible to derive accurate chemical information for stars brighter than \(G \sim 17\). These two powerful instruments, one in the North and one in the South, in combination with the Gaia mission will allow us to obtain full 6D phase-space information of a representative fraction of all the stars down to \(G \sim 21\) and chemical information for the brighter stars. Such chemical abundance information can be useful both to find merger remnants but perhaps even more importantly to characterize their progenitors (Johnston et al., 2008; Lee et al., 2015).

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\(^2\)http://www.sdss.org/

\(^3\)https://panstarrs.stsci.edu/

\(^4\)http://www.cosmos.esa.int/web/gaia

\(^5\)http://www.ing.iac.es/weave/about.html

\(^6\)http://www.4most.eu
3.2 Cosmological stellar halos

The goal of this chapter is to provide guidance on the observational strategies to map the Galactic halo with such multi-object spectrographs in order to recover merger debris. We wish to quantify the expected degree of inhomogeneity in the distribution of such debris. We will focus on choices regarding the use of different tracers and extent of surveys on the sky in order to maximize the recovery of the building blocks of the stellar halo. To this end, we explore the spatial and kinematics distribution of the debris in cosmological simulations of stellar halos, the effects of using different tracers such as red giant branch (RGB) or main sequence turn-off (MSTO) stars, and the impact of survey coverage on the sky. In Section 3.2 we describe the cosmological simulations of the stellar halo used for the analysis. In Section 3.3 we focus on the spatial distribution of accreted debris, with emphasis on the characterisation of its variation on the sky, and on the differences found by using different tracers. In Section 3.4 we explore line of sight velocity distributions and metallicity across the sky. In Section 3.5 we study the dependence of the recovery of the building blocks in terms of the area surveyed. We present our conclusions in Section 3.6.

3.2 Cosmological stellar halos

3.2.1 The simulations

We use the stellar halos modeled by Cooper et al. (2010) and Lowing et al. (2015). These authors have coupled the Aquarius dark matter cosmological simulations to the GALFORM semi-analytic model of galaxy formation. The version of GALFORM used is that of Font et al. (2011), which produces a good match to the observed properties of satellite galaxies, a scale that is particularly relevant to the work presented here. In a first step, suitably selected particles (typically the 1% most bound particles from halos hosting galaxies) from the very high resolution Aquarius simulations are assigned stellar populations according to the galaxy formation model. Based on those tagged particles, Lowing et al. (2015) then generated catalogs of individual stars.

These stellar halos have therefore fully formed via mergers and accretion. The main advantage of this set of models is that the properties of individual stars are available and can therefore be used in a straightforward fashion to motivate observational strategies or for comparison to surveys of the Galactic halo (Cooper et al., 2013, 2015; Xue et al., 2011). On the other hand, because these models are based on collisionless simulations, the systems do not include a particle-based disk component nor is there an in-situ component in the stellar halos. However, for the purpose of characterising the distribution of building blocks they are close to ideal because of their high resolution.

Our set of 5 stellar halos, Aq-A to E, all have different masses. This is at least in part a reflection of their dynamical mass being different. Table 3.1 lists their properties as well as the number of RGB and MSTO stars with magnitudes in the range $15 < g < 21$. Note that from here on we use $g$-band magnitudes and not Gaia $G$ because the Lowing et al. (2015) database provides magnitudes in the $ugriz$ system. Further, since Lowing et al. (2015) do not provide the stellar masses of the halos and the published catalogs only sample stars with $M_g < 7$, we have computed the stellar masses and luminosities of the halos and their building blocks ourselves. To this end, and like Lowing et al. (2015) we have used the Kennicutt IMF (Kennicutt, 1983) to estimate the fraction of stellar mass in the range $0.1 – 0.5776M_\odot$ (i.e.
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<table>
<thead>
<tr>
<th></th>
<th>$M_{200}$ ($10^{12} M_\odot$)</th>
<th>$M_{*}^{\text{halo}}$ ($10^8 M_\odot$)</th>
<th>$N_{\text{RGB}}$ ($\times 10^6$)</th>
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<tbody>
<tr>
<td>A</td>
<td>1.84</td>
<td>5.90</td>
<td>1.63</td>
<td>7.81</td>
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<tr>
<td>B</td>
<td>0.82</td>
<td>4.68</td>
<td>3.55</td>
<td>30.21</td>
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<tr>
<td>C</td>
<td>1.77</td>
<td>10.60</td>
<td>1.87</td>
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<tr>
<td>D</td>
<td>1.74</td>
<td>18.45</td>
<td>6.75</td>
<td>20.41</td>
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<tr>
<td>E</td>
<td>1.19</td>
<td>9.68</td>
<td>7.87</td>
<td>43.49</td>
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Table 3.1: Some properties of the Aquarius halos: virial mass $M_{200}$ from Cooper et al. (2010); stellar halo mass $M_{*}^{\text{halo}}$ (see text for details); and number of the RGB and MSTO stars with magnitudes in the range $15 \leq G \leq 21$.

starting from roughly the mass of a brown dwarf), to that in the range $0.62 - 0.7 M_\odot$: $f_{\text{low},M}$. From the catalog we have computed the total mass of all the stars in the latter range, $M_{0.62-0.7}$, and hence derived the stellar mass missing from the catalog as $M_{\text{low}} = f_{\text{low},M} * M_{0.62-0.7}$. We find $f_{\text{low},M} = 8.258$. We then added this mass to the total mass in stars obtained taking into account all the stars in the catalog with masses $m > 0.62 M_\odot$. On the other hand, to compute the luminosity, we first fitted a mass-luminosity relation in the $V$-band for stars of 10.1 Gyr with masses in the range $0.1 - 0.5776 M_\odot$. We found the mass-luminosity relation to follow the form $L_V \propto m^{7.3}$ (consistent with observations of nearby M dwarfs, Benedict et al., 2016). We then proceeded in the same way as for the stellar mass and computed the $f_{\text{low},L} = 0.629$. The resulting $L_{\text{low}}$ was then added to the luminosity of all the cataloged stars to derive the total luminosity of the stellar halos (and their building blocks).

The luminosity distribution of the building blocks of the different halos is shown in Figure 3.1. The dashed lines correspond to objects that have been disrupted, while the solid curves correspond to those that still depict a bound core without significant amounts of extra-tidal material. The criterion we have used to distinguish between these two classes is quite coarse: an object is disrupted if the size measured by the dispersion in the spatial direction ($\sigma = (\sigma_x^2 + \sigma_y^2 + \sigma_z^2)^{1/2}$) is larger than 10 kpc. Note the large number of small progenitors, with $M_V > -5$, a region that is observationally rather unconstrained and where galaxy formation models can differ significantly depending on their implementation of stellar feedback, UV background and reionization. Nonetheless, the amount of mass and stars these objects contribute is almost negligible, and so is their impact on the results presented here.

The luminosity function plotted in Figure 3.1 depicts some differences in comparison to that shown in Figure 9 of Cooper et al. (2010). Firstly because the version of GALFORM used is different (Font et al. instead of Bower et al.). Secondly, for the computation of the current luminosity of the satellites, we have used all the stars, including those that have already been stripped. Finally, because of our coarse characterisation of disrupted vs survivors, objects with a small bound core fall now in the category of disrupted building blocks. Table 3.2 summarizes the number of disrupted building blocks for different mass ranges for each of the Aquarius halos.
Figure 3.1: Cumulative distribution of the progenitors of the Aquarius stellar halos as a function of their absolute magnitude $M_V$. The dashed lines show the distribution for the disrupted satellites (with size larger than 10 kpc as measured by their dispersion in position), while the solid lines correspond to the survivors located within 280 kpc. For the computation of the absolute magnitude, all the stars originally belonging to the systems have been taken into account.

Table 3.2: Number of disrupted building blocks for different mass ranges for the Aquarius stellar halos.
3.2.2 Stars in the simulations

As described above, Lowing et al. (2015) re-sampled the tagged dark matter particles and associated stellar populations to produce stellar halos where every particle is a star with a given luminosity, according to the age and metallicity of the single stellar population it belongs to. Red giant branch (RGB) stars and main sequence turn off (MSTO) stars are highly complementary and often used as tracers in Galactic surveys. RGB stars are intrinsically bright and can be observed at large distances hence probing the outer regions of the halo. Here the mixing timescales are long and merger debris retains spatial coherence. Furthermore, this is also the region where dark matter is dominant, and RGB stars can thus be used to map its distribution and derive for example, the total mass of the Galaxy. On the other hand, MSTO stars can be easily identified by their blue colors, and being more abundant (by a factor 5 to 10 than RGB stars), they can be used to trace accretion events from smaller progenitors which produce lower surface brightness streams. In this chapter we will explore what kind of information can be retrieved by using these different tracers, and what kind of biases or limitations may be introduced by using either of these.

To this end, we have subdivided our sample by apparent magnitude into bright and faint RGB stars, and MSTO stars. Lowing et al. (2015) provide a flag to identify the RGB stars, while for the MSTO we consider those stars with $0.1 \leq (g-r) \leq 0.3$ and $M_g > 4$, i.e. our selection is slightly bluer than that used in Lowing et al. (2015). The bright RGB have $g$-band magnitudes $15 \leq g \leq 16$, and the faint RGB as well as the MSTO cover $16 \leq g \leq 21$. These choices are motivated by the types of samples that will be constructed for spectroscopic follow up. The bright RGB stars can be studied with high resolution, while the faint samples will likely be the targets of the low resolution studies, where accurate line of sight velocities can be obtained as well as basic chemical information, such as a metallicity and $\alpha$-enhancement for reasonable amounts of exposure and telescope time on 4m-class telescopes.

Because the Aquarius suite are dark matter only simulations, there is no preferred symmetry plane. Following Lowing et al. (2015) we assume the Galactic disk plane to be perpendicular to the minor axis of the moment of inertia tensor defined by the dark matter distribution in the inner 10 kpc. The Sun is located at $(X,Y,Z)=(8,0,0)$ kpc, with the $x$-axis along the major axis on this plane.

Figure 3.2 shows an example of a disrupted galaxy and how it is traced by the RGB and the MSTO stars. This object has a total stellar mass comparable to a small classical dwarf $8.4 \times 10^4 M_\odot$. The black dots in this figure denote all the stars in the progenitor, the cyan circles are the MSTO stars and the red circles are the observable RGB stars. From this example we note that the RGB stars are nearly all observable (large red circles) across the whole structure. On the other hand, only the MSTO stars located within a volume of $\sim 15 - 20$ kpc from the Sun (large cyan circles) are observable, highlighting as argued above that the two types of tracers are highly complementary.

Figure 3.3 shows the density distributions of different tracer stars on the sky. In this figure we have divided the sky into $60 \times 40$ bins along galactic longitude $l$, and sine of the galactic latitude $\sin b$, respectively. The left panel shows the distribution of faint RGB stars, with $16 \leq g \leq 21$, and depicts a large number of overdensities and streams for all halos. Note as well the presence of satellite cores, many of which are located at several tens of kpc. In this magnitude range, RGB stars can be found at distances of up to 100 kpc, or even beyond,
Figure 3.2: Spatial distribution of stars from a building block with stellar mass $8.4 \times 10^4 M_\odot$ of the Aq-A stellar halo. The cyan circles denote the MSTO stars while the red circles are the RGB stars, where those that are observable are shown with larger symbols. The black points are stars in neither of these two classes.
Figure 3.3: Sky density distributions for different tracers in the Aquarius stellar halos as indicated by the labels. The bright RGB have magnitudes $15 \leq g \leq 16$, and the faint RGB as well as the MSTO cover $16 \leq g \leq 21$.

depending on their intrinsic luminosity. In contrast, the middle panels show that the spatial distribution of bright RGB stars is relatively smooth. This is because the volume probed by this sample extends up to about 40 kpc from the Sun, and this is clearly apparent in the large overdensity seen in the middle of the panels for all halos, which corresponds to the centre of the simulated halo (located at 8 kpc from the observer). The faint MSTO stars shown in the panel on the right, depict a similar distribution as the sample of bright RGB stars, as expected since they probe a similar volume. Because of their larger numbers, some overdensities are more readily apparent and thus have a higher statistical significance.

### 3.3 Debris from building blocks on the sky

Figure 3.4 shows the distribution of the progenitors with different colors for the stellar halo in Aq-A. The top panel corresponds to the RGB stars, and the bottom to the MSTO stars. These tracers are separated in apparent magnitude bins as a way of slicing through distance from the Sun. The small scale lumpiness which are apparent in the MSTO sample is caused by the resampling method of the dark matter particles present in the original Aquarius simulations.

The first point to notice is that both bright MSTO and RGB stars trace the more massive progenitors whose spatial distribution is well mixed. Faint RGB stars, on the other hand, reveal many spatially coherent streams for all Aquarius halos, although this varies slightly from halo to halo. As expected, the faintest magnitude bin for the MSTO sample depicts similar behaviour as the third brighter bin of the RGB stars. Further examples of the distribution
of RGB stars on the sky for the different Aquarius halos are given in the Appendix (Section 3.7.1).

To quantify the degree of variance in the number of progenitors on the sky in Figure 3.5 we have plotted the number of detectable progenitors per pixel for all the Aquarius stellar halos. We say that a progenitor is detectable if more than 5 of its stars can be found in the bin on the sky. As in Figure 3.3 we have used different tracers, namely faint RGB, bright RGB and faint MSTO in the left, middle and right hand side panels respectively.

Figure 3.5 shows that the largest number of different progenitors are found at the center of the halo, and this number ranges for example for Aq-A from 49 if traced by MSTO stars and from 27 for RGB stars, while for example for Aq-C the number of progenitors traced is 66 and 39 for MSTO and RGB stars respectively. Therefore, the first conclusion from this figure is that the MSTO stars can trace more detectable progenitors across the whole sky than the RGB stars, even though the fainter RGB stars probe a larger volume. The reason is their sheer number. Note that with our requirement that a progenitor is detectable if it has at least 5 stars in a sky bin, we effectively introduce a bias for the RGB sample: structures from systems such as the ultra-faint dwarf galaxies, which often have just a handful of RGB stars will not be considered as observable. This is why, and although there may be many more streams in the outer regions that could potentially be probed by RGB stars, they are not apparent in our plots.

The next interesting question is how often is a field dominated by a single progenitor or building block, and what is the distribution of such pixels on the sky. In Figure 3.6 we have plotted for the Aq-A stellar halo the purity of each pixel on the sky, which is defined as $p_{ij} = \frac{\max(n_{ij}^k)}{\sum n_{ij}^k}$, where $i$ and $j$ are the index of the bin along longitude and latitude, and $n_{ij}^k$ is the number of the stars in $ij$th bin from $k$th progenitor. For this figure we have taken into account all progenitors (also those contributing less than 5 stars to a given sky bin). We separate this into different magnitude ranges using RGB stars and MSTO stars as tracers. The higher the purity, the higher the fraction of stars in that bin that are from a common progenitor.

This figure shows that especially the fainter RGB stars trace well spatially coherent streams (this was also apparent from Figure 3.4), and this is revealed by the high purity of the pixels on the sky. On the other hand, the MSTO stars reveal the highest purities in the magnitude ranges considered in regions towards the halo centre. For the faintest magnitude bin, they also reveal streamy features. These results hold for most of the Aquarius stellar halos as can be seen in the Appendix (Section 3.7.1) for the RGB tracers, except for Aq-E. In this case, a very massive building block dominates the distribution on the sky for a range of magnitudes, both in the RGB and MSTO samples.

### 3.4 Kinematic and metallicity characterisation

#### 3.4.1 Galactocentric radial velocity distribution

Figure 3.4 shows that spatial information alone is often not enough to recover much merger debris. We therefore turn to what may be obtained from spectroscopy, namely line-of-sight velocities and metallicity or chemical abundance information. Stars from accreted satellites
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Figure 3.4: The distribution of stars on the sky for different magnitude ranges for Aquarius halo A, for RGB and MSTO stars. The colors are coded according to the progenitor IDs. The small scale lumpiness apparent in the MSTO sample, is due to the resampling method of the dark matter particles present in the original Aquarius simulations.
Figure 3.5: The distribution of the number of progenitors in the sky bins. Only progenitors with at least 5 stars in one bin are taken into account. The left, middle and right panels show the distributions traced by respectively, the faint RGB, the bright RGB, and the MSTO stars. The white areas/bins correspond to regions where there is no progenitor contributing more than 5 stars traced by the specific type of star.
RGB - purity

MSTO - purity

Figure 3.6: The purity of the bins on the sky traced by RGB and MSTO stars for different magnitude ranges in the Aq-A stellar halo. At the galactic center, an MSTO star would have an apparent magnitude of $g \sim 18.5$, while for an RGB with absolute magnitude $M_g=0.5$, then $g \sim 15$. 
3.4 Kinematic and metallicity characterisation

will move coherently through space and therefore will have similar line-of-sight velocities at a given physical location.

Figure 3.7 shows the distribution of radial velocity $V_{GSR}$ in the Galactic standard of rest frame for the RGB (top) and for the MSTO stars (bottom) for Aq-A. The Galactocentric l.o.s. velocity is defined as

$$V_{GSR} = V_{LSR} + 220 \sin(l) \cos(b)$$  \hspace{1cm} (3.1)

where $V_{LSR}$ is the radial velocity relative to the Local standard of rest frame. Note that this velocity has been obtained from the simulations assuming an observer located with a Galactocentric distance 8 kpc. The figures show that there is no mean rotation in the halo but that there are regions with significantly different average Galactocentric velocities, marked in red or in blue. This implies that most of the stars in those regions are moving with similar velocity, and hence could be streams. Comparison to Figure 3.6 shows that in fact, those bins correspond well to regions dominated by a single progenitor or building block (i.e. high purity).

The opposite is not true, not all high purity bins in Figure 3.6 depict a deviant velocity as can be seen from inspection in Figure 3.7. This is likely because along a given line-of-sight several streams from the same object can be found, leading to an average radial velocity distribution that is relatively smooth.

We explore the kinematics further in Figure 3.8, where we have plotted the velocity dispersion in a given bin on the sky for different magnitude ranges, again for the RGB and MSTO stars. As in the previous figure, we can conclude that not all high purity bins can be associated to streams, as the velocity dispersion of such bins is relatively large, especially towards the center of the halo. It is clear however, that the fainter the RGB stars, the lower the value of the velocity dispersion. This can be indicative of structure but it can also be the result of the dynamical state, as the dispersion must decrease as the tracer population reaches the edge of the system (see e.g. Battaglia et al., 2005; Xue et al., 2008). On the other hand, if a structure has deviant mean l.o.s. velocity, then it shows as a cold, low-velocity dispersion, kinematic structure. An example of this is the feature with $l \sim -60^\circ$ and $-1 < \sin b < -0.5$ for the faintest MSTO stars.

These general trends are valid for all the Aquarius stellar halos. However some of the halos such as Aq-C and Aq-D contain large narrow streams on the sky well-traced by RGB stars, and this results in clear imprints in their distribution of line-of-sight velocities on the sky, and in particular on very low values of the velocity dispersion as can be seen in the Appendix (Section 3.7.2).

In Figure 3.9 we show the distribution of l.o.s. velocity dispersions for the different magnitude bins and for the two tracer populations again for Aq-A. These histograms show that the most likely (even mean) $\sigma_{GSR}$ is in the range of 100 - 180 km/s, both for RGB and MSTO samples. A small fraction of the bins have low velocity dispersions, and only for the RGB sample and for the brightest MSTO stars are there bins with dispersions lower than 40 km/s. This means that most of the bins on the sky, even when slicing through magnitude space, contain debris from several overlapping streams or structures.

This is more clearly visible in Figure 3.10, where we have plotted an example of the l.o.s. velocity distribution for all the RGB and MSTO stars in a particular bin on the sky
Figure 3.7: Distribution of average Galactocentric radial velocity $V_{GSR}$ on the sky using RGB and MSTO stars as tracers.
Figure 3.8: Distribution of the dispersion in Galactocentric radial velocity $V_{GSR}$ on the sky using RGB and MSTO stars as tracers.
(with coordinates $l = 81^\circ$, $\sin b = -0.575$). What we see here is typical of what is found for other bins. The total velocity dispersion for this bin is $\sigma_{GSR} \sim 150$ km/s, but the distribution is far from Gaussian and shows several peaks that are associated to different structures. In particular, and as expected, the RGB sample shows a distribution that has more structure than the MSTO, and this is likely due to the fact that the MSTO sample probes the inner galaxy, where mixing is stronger, and hence the individual streams are harder to see without additional (tangential) velocity information.

It is interesting to compare these results to the work of Schlaufman et al. (2009), who using the SDSS/SEGUE and MSTO as tracers, have detected an important number of cold kinematic structures, with dispersion up to 50 km/s. Figure 3.9, which corresponds to the MSTO stars sample, would seem to suggest that such cold structures are rather rare in our simulated halo. However, it is important to note that the structures detected by Schlaufman et al. (2009) were identified by using an algorithm that compares the distribution of velocities along a given line of sight with a kinematically smooth model of the inner halo. Effectively, Schlaufman et al. (2009) have been able to detect the individual peaks that are seen in Figure 3.10.

Furthermore, as discussed earlier there are some variations in the distribution of l.o.s. velocity dispersions on the sky from halo to halo in our simulations (see Appendix Section 3.7.2 for details). For example, for Aq-B and Aq-E the most likely velocity dispersion in a given bin is $\sim 60 - 90$ km/s, and there are many bins, especially for the faint RGB stars, with dispersions lower than 30 km/s. These lower most likely values of the velocity dispersions in Aq-B and Aq-E compared to Aq-A (and also Aq-C and D) is due to their lower total mass. On the other hand, Aq-C and Aq-D show similar characteristics as Aq-A.

**3.4.2 Metallicity distribution**

Spectroscopy of intermediate resolution on a 4m class telescope allows also the determination of metallicities within a reasonable amount of telescope time for stars with apparent $g$-band magnitudes in the range 15 to 21.

In Figure 3.11 we show the averaged metallicity distribution in bins over the whole sky for Aq-A. The metallicity is defined as $[m/H] = \log_{10}(Z/Z_\odot)$ where $Z_\odot = 0.02$. The bin size and the magnitude ranges here are the same as those in Figure 3.8.

Notice that this map is richer in structure than the integrated l.o.s. velocity maps. It resembles to some extent the map showing the purity distribution in Figure 3.6. The more metal-rich stars (in red) are found towards the center, as well as in some of the streams on the sky. The center is more metal-rich because it is where the stars from massive progenitors, which have sunk in towards the center of the halo as they were accreted, are deposited. This leads to a metallicity gradient over the sky especially for the bright RGB and for the MSTO samples: regions around the halo center are more metal-rich than those at higher latitudes, although one could probably describe this better in terms of a dual component halo: a core that is metal-rich and then a background which on average has lower metallicity and some amount of substructure. Note as well that there is a slight indication of a metallicity gradient with distance, especially if MSTO stars are used as tracers. This could be due to a true gradient, as it is also visible for RGB stars but is less prominent than for MSTO. The reason for this could be that the MSTO trace smaller progenitors better, which are expected to be
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Figure 3.9: Distribution of the dispersion $\sigma_{GSR}$ in km/s for all the bins in the sky, using RGB (red) and MSTO (black) stars.

Figure 3.10: Radial velocity $V_{GSR}$ distribution of the tracer stars within a bin on the sky located at $l = 81^\circ$, $\sin b = -0.575$ for the Aq-A halo. The red line shows the distribution of $V_{GSR}$ of the RGB stars, and the black line represents that of the MSTO stars.
Figure 3.11: Distribution of average metallicity over the sky for the Aq-A stellar halo.
3.5 Observational strategy

We seek to determine how the recovery of the building blocks of the stellar halo of our Galaxy can be maximized. In this section we explore using the simulated stellar halos how this recovery rate depends on area surveyed on the sky, the different tracers used, and the orientation on the sky. We recall that, since there is no disk component/preferred plane in the Aquarius simulations, the orientation of the reference frame is arbitrary. This should be borne in mind when we discuss survey areas centered around e.g. the north and south galactic poles, or the anticenter direction. The observer is at 8 kpc from the halo center.

Figure 3.12 shows the fraction of the detectable progenitors as function of surveyed area and for the different tracers for Aq-A (left) and Aq-C (right). This fraction is defined as the ratio of the number of the detectable progenitors (with more than 5 tracer stars in the region of the sky considered) to the total number of progenitors in the region. Here only progenitors with stellar mass greater than $1.7 \times 10^4 M_\odot$ are considered. The top panels corresponds to the faint RGB stars subset, the middle to the bright RGB and the results using MSTO stars are shown in the bottom panels. We have also separated the contribution of the progenitors according to their stellar mass: blue corresponds to $1.7 \times 10^4 < M_*/M_\odot < 10^5$, purple to $10^5 < M_*/M_\odot < 10^6$ and green to $M_*/M_\odot > 10^6$. The shaded regions indicate the variation in the fraction recovered for each sky coverage caused by considering different orientations.

Both RGB samples behave similarly, with the fraction of detectable progenitors increasing nearly linearly with coverage. Those progenitors with $M_*/M_\odot < 10^6$ (purple and blue) have a similar dependence with sky coverage while the more massive ones show a shallower (and hence weaker) dependence with sky coverage. This is likely because these progenitors contribute stars across the full sky, and hence its stars can be found for nearly all coverages. Note that on average, the faint RGB stars are able to trace a higher fraction of the progenitors, reaching also those that contribute stars at greater distances, as large as 100 kpc. In outer part of the halo, those progenitors are not mixed as much as those in the inner part, implying that the larger the area the higher the probability of finding more progenitors. There is an interesting difference between halos Aq-A and Aq-C for the more massive progenitors, in

more metal poor on average. It is clear from this plot that there is significant directionality dependence, and for example, one would not claim such a gradient if probing a band along a great circle from $l = -120, \sin b = -0.5$ to $l = 120, \sin b = 0.5$.

These findings also apply to the Aq-B halo (see Appendix Section 3.7.3 for details). Aq-C depicts a shallower gradient than Aq-A or Aq-B as the regions around the halo centre are not very metal-rich. The highest metallicity stars for these halo are found in a well-defined stream on the sky. For Aq-D the metallicity distribution on the sky is rather different, with the more metal-rich RGB stars distributed over the whole sky seemingly avoiding the center of the halo, except at the faintest magnitudes. On the other hand, for Aq-E both RGB and MSTO clearly reveal a large metallicity gradient, with the brighter stars being almost exclusivley metal-rich. Little small substructure is apparent on the metallicity distribution on the sky for this halo. These comparisons reveal that each halo is rather unique and that it is not trivial to draw firm predictions about what to expect to the Milky Way’s halo. Only by surveying a large fraction of the sky will we be able to obtain a complete view of the Galactic halo metallicity distribution.
Figure 3.12: The fraction of detectable progenitors versus sky coverage using different tracers for the Aq-A (left) and Aq-C (right) stellar halos. The shaded regions indicate the variance in the fraction with varying orientation: towards the north and south poles, and anticenter. From top to bottom, the tracers used are the fainter RGB, the brighter RGB and the MSTO stars respectively.
the sense that a higher fraction of these is detectable using RGB stars for Aq-C than for Aq-A. This is because Aq-A has a smaller number of such progenitors than Aq-C, 9 vs 17 as indicated in Table 3.2, implying that the chances of finding their stars depends on the specific spatial distribution of a smaller number of objects, which thus implies an increase in the stochasticity of their degree of detectability.

In the case of MSTO, there is a steep increase with sky coverage until about $\sim 5,000$ sq.deg. after which the fractions appear to saturate. The reason is that the MSTO stars can only trace progenitors that have contributed within a small volume (in comparison to the faint RGB stars). These stars are thus nearly homogeneously distributed over the sky as shown in Figure 3.5, leading to a stable recovery fraction with sky coverage, provided this is sufficiently large.

It is interesting to note that the bright RGB and the faint MSTO behave similarly for the more massive progenitors. This is because their debris occupy a relatively large volume nearly homogeneously and the two samples are covering a similar distance range. On the other hand, it seems better to use MSTO stars to trace smaller progenitors in the inner halo. This is simply due to their higher number abundance.

The variance caused by different orientations is not very large, and mostly of 0.2 in amplitude on the recovered fraction. Note however, that for the more massive progenitors, the variance is much smaller and this again is due to the much more homogeneous distribution of their debris. This can also be seen from Figure 3.5, which shows that there are more detectable progenitors with faint RGB stars and MSTO stars towards the galactic anticenter than the North/South pole, at least in our assumed orientation of the reference frame.

Figure 3.13 shows the different contributions of the detectable progenitors obtained using the different tracers for Aq-A. We find that almost all those progenitors detectable by bright RGB stars can be recovered by the other two tracers. There is a larger number of progenitors traced only by faint RGB and which become only apparent for sufficiently large sky coverage (of at least 10,000 sq.deg.). On the other hand, there are more progenitors missed for low sky coverage if one uses bright RGB stars instead of MSTO, although both tracers probe a similar volume. The difference is due to the larger number of MSTO stars and our definition of detectability. It is interesting that most progenitors will be recovered, given our condition for detectability, in all samples.

3.6 Discussion and Conclusions

We have explored the distribution of accreted stars in five stellar halos from the Aquarius simulations as modeled by Lowing et al. (2015). Our aim was to guide choices for the next generation massive spectroscopic surveys such as WEAVE and 4MOST regarding the use of different tracers, depth and sky coverage. To this end we used RGB stars and MSTO stars in the magnitude range $15 < g < 21$ from the online catalogs from Lowing et al. (2015).

Unsurprisingly we find that the RGB stars are the better tracers as they can be used to find building blocks out to about 100 kpc. For these tracers, the fraction of building blocks that can be recovered increases almost linearly with sky coverage. Therefore, the larger the sky coverage is, the better for characterising the merging history of the halo. Depending slightly on the orientation, we find that a minimum of 10,000 sq.deg. is necessary to find at least half
Figure 3.13: Comparison of detectable progenitors as function of sky coverage for different tracers, and for the orientation towards the “north pole”. The top, middle and bottom panels show the comparison between the bright and faint RGB stars, the bright RGB and MSTO, and the faint RGB and MSTO stars respectively. The red and dark green parts represent the number of progenitors detectable with either of the two tracers considered in each panel, but not by both. The light green represent the number of the progenitors detectable by both tracers.
3.6 Discussion and Conclusions

of the building blocks, where this fraction is a bit dependent on the specific history of the halo.

On the other hand, because of the lower intrinsic luminosity of MSTO stars, there is no strong dependence in the detectability on the sky coverage beyond $\sim 5,000$ sq.degrees. This is because their large number allows to trace a high fraction of all nearby progenitors present in the volume accessible to these stars. For the progenitors with stellar mass $M_* < 1.6 \times 10^6 M_\odot$, the fraction traceable by MSTO stars is $\sim 70\%$, while for those more massive it is $\sim 40\%$. Increasing the sky coverage does not help in finding more building blocks.

This implies that, given the constraints, it is advisable to use RGB stars as the main target in large spectroscopic surveys whose coverage should be at least 10,000 sq.degrees. Low resolution studies will reveal significant structure in the kinematics and metallicity distribution over the sky. For high resolution studies, one is restricted to the bright RGB sample, and in that case the recovery fraction is lower for smaller coverage, but at least 50% of building blocks with stellar mass comparable to the present day classical dwarf spheroidals, can be traced in a survey of 5,000 sq.degrees.

We find that differences in orientation on the sky of the survey (i.e. towards the north/south pole and galactic anticenter from our vantage point of view) have little impact. Although we have reached these conclusions using a coordinate system in which the Sun is along the major axis of the host dark matter halo (as specified in the mock catalog by Lowing et al., 2015), we find very similar results if we set the observer on $y$-axis at a Galactocentric distance 8 kpc.

These conclusions have been reached considering all building blocks with masses greater than $1.7 \times 10^4 M_\odot$. Lower luminosity objects, comparable to the ultra-faint dwarf galaxies, will require the use of MSTO stars to detect them, as they will contain just a handful of RGB stars. It seems that the best strategy for such objects is to develop a strategy for targeted observations rather than an unbiased survey, as we have explored in this chapter. It seems reasonable to allocate a certain fraction of the spectroscopic survey’s time to specific streams or structures identified from e.g. photometric surveys, given the utmost importance of such systems in characterizing cosmology and galaxy formation and evolution at the lowest mass end.

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Aq-B and Aq-C

Figure 3.14: The distribution of RGB stars on the sky for different magnitude ranges for Aquarius halos B and C. The colors are coded according to the progenitor IDs.

Aq-D and Aq-E

Figure 3.15: Same as Figure 3.14 for Aq-D and E (left and right respectively).

3.7 Appendix

3.7.1 Distribution on the sky for halos Aq-B to Aq-E

In this Appendix we include plots showing the distribution of RGB stars for Aq-halos B, C, D and E as function of magnitude in Figures 3.14 and 3.15. We then show in Figure 3.16 and 3.17 the distribution of purity: the fraction of stars in a given bin on the sky that originate in the same progenitor for the same set of halos and also using RGB stars as tracers.
3.7 Appendix

Aq-B and Aq-C - purity

Figure 3.16: The purity of the bins on the sky traced by RGB stars for different magnitude ranges in the Aq-B (left) and C (right) stellar halos.

Aq-D and Aq-E - purity

Figure 3.17: Same as Figure 3.16 for Aq-D (left) and E (right) stellar halos.

3.7.2 Kinematics across the sky for halos Aq-B to Aq-E

In this Appendix we include plots showing the distribution of l.o.s. velocity dispersions on the sky for the RGB stars in Aq-halos B, C, D and E as function of magnitude in Figures 3.18 and 3.19. We then show in Figures 3.20 and 3.21 histograms of the distribution of l.o.s. velocity dispersions using RGB and MSTO stars.

3.7.3 Metallicity distribution across the sky for halos Aq-B to Aq-E

In this Appendix we include plots showing the distribution of metallicity on the sky for the RGB stars in Aq-halos B, C, D and E as function of magnitude in Figures 3.22 and 3.23.
Figure 3.18: Line-of-sight velocity dispersion maps for RGB stars for different magnitude ranges in the Aq-B (left) and C (right) stellar halos.

Figure 3.19: Same as Figure 3.18 for Aq-D (left) and E (right) stellar halos.
3.7 Appendix

**Aq-B and Aq-C - $\sigma_{GSR}$ (km/s)**

Figure 3.20: Distribution of line-of-sight velocity dispersion for RGB (red) and MSTO stars (black) for different magnitude ranges in the Aq-B (left) and C (right) stellar halos.

**Aq-D and Aq-E - $\sigma_{GSR}$ (km/s)**

Figure 3.21: Same as Figure 3.20 for Aq-D (left) and E (right) stellar halos.
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**Aq-B and Aq-C - metallicity**

![Metallicity maps for RGB stars for different magnitude ranges in the Aq-B (left) and C (right) stellar halos.](image1)

**Aq-D and Aq-E - metallicity**

![Metallicity maps for RGB stars for different magnitude ranges in the Aq-D (left) and E (right) stellar halos.](image2)

Figure 3.22: Metallicity maps for RGB stars for different magnitude ranges in the Aq-B (left) and C (right) stellar halos.

Figure 3.23: Same as Figure 3.22 for Aq-D (left) and E (right) stellar halos.