Formation of In Situ Stellar Haloes in Milky Way-Mass Galaxies

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ABSTRACT
We study the formation of stellar haloes in three Milky Way-mass galaxies using cosmological SPH simulations, focusing on the subset of halo stars that form in situ, as opposed to those accreted from satellites. In situ stars in our simulations dominate the stellar halo out to 20 kpc and account for 30 – 40 per cent of its total mass. We separate in situ halo stars into three straightforward, physically distinct categories according to their origin: stars scattered from the disc of the main galaxy (“heated disc”), stars formed from gas smoothly accreted onto the halo (“smooth”-gas) and stars formed in streams of gas stripped from infalling satellites (“stripped”-gas). We find that most belong to this latter category. Those originating in smooth gas outside the disc tend to form at the same time and place as the stripped-gas population, suggesting that their formation is associated with the same gas-rich accretion events. The scattered disc star contribution is negligible overall but significant in the Solar neighbourhood, where \(\gtrsim 90\) per cent of stars on eccentric orbits once belonged to the disc. However, the distinction between halo and thick disc in this region is highly ambiguous. The chemical and kinematic properties of the different components are very similar at the present day, but the global properties of the in situ halo differ substantially between the three galaxies in our study. We conclude that, in our simulations, the hierarchical buildup of structure is the driving force behind not only the accreted stellar halo, but also those halo stars formed in-situ.

Key words: dark matter: structure – galaxies: haloes – methods: numerical

1 INTRODUCTION
Following Searle & Zinn (1978), much observational and theoretical work on the Milky Way’s stellar halo has focussed on the tidal stripping and disruption of satellite galaxies. The idea that galactic stellar haloes are built mainly by accretion is well supported by theoretical predictions of the standard dark energy/cold dark matter (ΛCDM) cosmogony (White & Frenk 1991; Bullock & Johnston 2005; Cooper et al. 2010) and direct evidence of tidal streams around nearby galaxies (Belokurov et al. 2006; McConnachie et al. 2009; Martínez-Delgado et al. 2010). However, recent work has shown that some aspects of the Milky Way’s stellar halo may be difficult to explain by accretion alone, notably its central concentration and uniformity across the sky (Bell et al. 2008; Carollo et al. 2007; Helmi et al. 2011; Cooper et al. 2011; Xue et al. 2011; Deason et al. 2011).

Meanwhile, hydrodynamical simulations have predicted a distinct ‘in situ’ halo component, defined (loosely) as having formed bound to the Milky Way itself rather than to any of its hierarchical progenitors (Abadi et al. 2003; Brook et al. 2004; Zolotov et al. 2009; Font et al. 2011; Tissera et al. 2013). Such haloes are a natural outcome of the ΛCDM model, which predicts that the vast majority of stars in a galaxy like the Milky Way form from the cooling of gas trapped by the galaxy’s own dark matter potential (White & Rees 1978; White & Frenk 1991). The bulk of these in situ stars can be identified with the kinematically cold, rapidly rotating Galactic disc, but the proto-Milky way may also have suffered strong perturbations from satellites and quasi-secular rearrangement (e.g. ‘disc flips’; Bett & Frenk 2012), or even wholesale destruction and regrowth before the majority of present-day disc stars were formed (e.g. Sales et al. 2012; Aumer et al. 2013; Aumer & White 2013). If real galaxies pass through such messy stages of formation, it seems likely that a significant fraction of stars formed in the early Galaxy would now have highly eccentric orbits.

Recent simulations find that these in situ processes create haloes that are more concentrated, metal-rich and oblate than those formed by accreted stars (McCarthy et al. 2012).
This supports the hypothesis of a transition between an in situ and an accreted halo as an explanation for the apparently ‘bimodal’ properties of halo stars observed in the Milky Way (Carollo et al. 2010; Beers et al. 2012; Tissera et al. 2014).

However, quantitative results concerning the origin of in situ halo stars and their importance relative to accreted stars are still very uncertain. Where they rely on simulations, such conclusions can be particularly sensitive to the numerical methods used. Starting from identical initial conditions, current state-of-the-art simulations predict substantially different properties for the bulk of the in situ stellar mass in Milky Way-like dark matter haloes (e.g. Scannapieco et al. 2012; Aumer et al. 2013), not just the few percent that might be identified with an in situ halo. Moreover, the properties of in situ haloes may be much more sensitive to certain modelling choices than those of massive stellar discs, including prescriptions for star formation and the treatment of the multi-phase interstellar medium (for example, the mixing of hot and cold in galactic winds, tidal streams and cold clumps of free-falling gas).

Here we analyse the origin of in situ halo stars using three Milky Way-scale simulations run with the code described in Parry et al. (2012), one of the participants in the Aquila comparison project (Scannapieco et al. 2012). Two of the three dark matter haloes we simulate have also been simulated by Tissera et al. (2012, 2013, 2014) using different ‘sub-grid’ recipes for star formation and feedback but an otherwise similar hydrodynamic solver and identical initial conditions. We define what we mean by in situ halo stars in a straightforward and easily reproducible way. Careful definitions are particularly important for this problem because the concept of an in situ halo straddles an extremely fuzzy boundary between all the conventional Galactic components – disc, thick disc, bulge and halo.

We proceed as follows. We describe our simulations in Section 2. In Section 3 we explain how we identify in situ halo stars and in Section 4 we examine their origins. Section 5 describes the present-day properties of our in situ halo. Section 6 investigates the satellite progenitor of in situ stars formed from stripped gas. Our conclusions are given in Section 8.

### 3 SAMPLE DEFINITION

The first step in defining our stellar halo sample is to identify all stars belonging to the central (Milky Way-analogue) galaxy at the present day (redshift $z = 0$). We choose stars that lie within a radius $r_{200}$ which encloses a sphere of mean density 200 times the critical value for closure ($r_{200} = 227$ kpc for Aq-C and Aq-D, 202 kpc for Aq-E). From this sample, we isolate the halo by excluding stars that belong to satellite galaxies within $r_{200}$ and stars that belong to the main galaxy disc and bulge, as follows.

Satellite dark matter haloes and their galaxies are isolated using a version of the subfind algorithm (Springel et al. 2001) adapted by Dolag et al. (2009) to identify self-bound substructures, taking into account the internal energy of the gas when computing particle binding energies. All star particles bound to dark matter subhaloes at $z = 0$ are excluded from our halo star sample.

The central galactic disc is identified by finding stars on orbits that are approximately circular and that lie close to...
a plane normal to the net angular momentum vector of the whole stellar component. A coordinate system is chosen such that the net angular momentum vector of all stars within $0.2r_{200}$ points in the positive $z$-direction. The circularity of each star’s orbit is then defined as

$$\xi_{E} = \frac{J_{z}}{J_{circ}(E)},$$

where $J_{z}$ is the $z$ component of the star’s specific angular momentum and $J_{circ}(E)$ is the specific angular momentum of a star with the same binding energy on a circular orbit. All stars with $\xi_{E} > 0.8$ are identified with the central galactic disc and excluded from our halo star sample.

Fig. 1 shows the distribution of stellar circularity as a function of radius in our three simulations. A concentration of corotating stars on near-circular orbits extending to $\sim 30$ kpc is obvious in all cases, which we identify with the thin disc. A number of streams on pro- and retrograde orbits are also visible at large radii.

At $r \lesssim 5$ kpc the density of stars on non-circular orbits is comparable to the density of stars in the disc. We identify this complex region with a galactic bulge. To simplify our definition of the stellar halo, we exclude all stars with $r < 5$ kpc, regardless of circularity. This cut is easy to apply to both models and data. It also follows the loose convention of most Milky Way stellar halo work, in which stars more than a few kiloparsecs interior to the Solar Neighbourhood are excluded (the exception being those high above the disc plane) even though the inward extrapolation of a canonical $r^{-3}$ density profile would predict a substantial mass of halo stars in the centre of the Galaxy (see also the discussion in Cooper et al. 2010).

Fig. 1 further separates star particles into accreted (middle row) and in situ (bottom row) according to whether or not they are bound to the main branch progenitor of each dark matter halo at the first snapshot after their formation. Star particles that are first bound to a dark matter halo other than the main progenitor are considered as accreted, even if they form in a subhalo of the main branch (i.e. if they form in a satellite galaxy of the Milky Way analogue) and are subsequently stripped\(^1\). Table 2 summarizes the total mass of the stellar halo and the relative proportion of in situ stars.

Fig. 2 shows the mean density of accreted and in situ halo stars in spherical shells centred on the galaxy. The profile of the in situ halo has a similar shape and amplitude in all three simulations, with a slight steepening evident in the ‘bulge’ region of Aq-C. In both Aq-C and Aq-D the accreted halo stars are less centrally concentrated than the in situ component, with a mild break due to accreted stars alone at $70 < r < 90$ kpc, while in Aq-E the two components are almost indistinguishable. The accreted - in situ transition in these profiles at $\sim 20$ kpc is consistent with the average for Milky Way analogues in the GIMIC simulation (Font et al. 2011).

Aq-D and Aq-E have ‘thick’ discs with a high degree of non-circular motion, apparent in the top row of Fig. 1 as a high density of stars at $0.5 < \xi_{E} < 0.8$ and $5 < r < 20$ kpc.

\(^1\) This is an important difference with the work of Tissera et al. (2013, 2014), who included stars formed in bound satellites within $r_{200}$ in the in situ halo as part of their ‘endo debris’ category.

| Mass \((10^{9}M_{\odot})\) | Aq-C | Aq-D | Aq-E |
|--------------------------|------|------|------|
| Disc \((r > 5 \text{ kpc, } \xi_{E} > 0.8)\) | 3.0 | 4.3 | 4.3 |
| Bulge \((r < 5 \text{ kpc})\) | 34.5 | 21.9 | 25.2 |
| Halo \((r > 5 \text{ kpc, } \xi_{E} < 0.8)\) | 4.6 | 8.4 | 6.8 |
| In situ halo fraction | 37% | 33% | 41% |

According to the aforementioned cuts on circularity and radius, we classify these as halo stars. However, examining the variation of the circularity distribution with height above the disc plane reveals that these stars simply make up the low-circularity tail of a continuous distribution. The fraction of stars on circular orbits is highest close to the plane.

The most important question for this paper is not the origin of thick disc stars, but whether or not they can, or should, be distinguished from those in the halo. Fig. 1 shows that accreted stars can make a significant contribution to the ‘disc’. In Aq-D, they contribute mainly to the ‘thin’ disc – the thick disc is formed in situ. In Aq-E, accreted and in situ ‘disc’ stars contribute at a similar ratio over a wide range of circularity and radius. Clearly there are no universal criteria to separate thick discs from thin discs or stellar haloes, either kinematically or in terms of origin. Observational distinctions between the thin disc, thick disc and halo of the Milky Way are just as ambiguous (Bovy et al. 2012). Hence, we choose not to introduce any further cuts to separate thick disc and halo stars. This should be kept in mind when comparing our results to observations.

4 THE ORIGIN OF IN-SITU STARS

In this section we look in more depth at the origin of the in situ component of the stellar halo. The density of this component exceeds that of accreted halo stars in the inner $\sim 20$ kpc of our galaxies. It may thus be very important for spectroscopic observations of halo stars in the Solar Neighbourhood and in surveys of main-sequence turnoff stars within a few kiloparsecs of the Milky Way disc plane.

In order to trace how in situ stars formed in our simulations, we separate them into three disjoint subcategories:

(i) ‘heated disc’ stars, which met the thin disc circularity criterion when they were formed, but are not in the disc at $z = 0$;
(ii) stars formed from ‘stripped gas’, brought into the main dark matter halo bound to a subhalo and subsequently stripped by tidal forces or ram pressure;
(iii) stars from ‘smoothly accreted gas’, which enters the main dark matter halo through direct (smooth) accretion.

Cases (ii) and (iii) are easily distinguished by tracing the dark matter halo membership history of the parent gas particle for each star particle. The gas from which heated
Figure 1. The distribution of stars in radius-circularity space for Aq-C (left column), Aq-D (centre column) and Aq-E (right column). Panels in the top row include all stars bound to the main dark matter halo ($r < 90$ kpc), while the middle and bottom rows include only accreted and in situ stars respectively. Dashed horizontal lines indicate the circularity cut used to define disc stars. Dashed vertical lines mark the 5 kpc cut in radius used to define bulge stars. All stars outside these regions are classified as halo stars. The colour scale corresponds to the logarithm of the number of star particles.

Table 3. Breakdown of all in situ halo stars into three subtypes, according to their formation mechanism.

| Subtype               | Aq-C | Aq-D | Aq-E |
|-----------------------|------|------|------|
| Heated disc           | 2.8% | 26.0%| 31.0%|
| Stripped gas          | 59.8%| 56.7%| 56.9%|
| Smoothly accreted gas | 37.3%| 17.3%| 12.1%|

Disc stars form must originally have either been stripped from a subhalo or smoothly accreted, so these stars could also be classified into the second or third categories. However, in this case it is the fact that they formed in the thin disc and were scattered out of it, rather than how their parent gas particle arrived in the disc, that we consider to be most important.

The fraction of in situ halo stars in each category is shown in Table 3. It is clear that there is a large variation between the three simulations, although the in situ stars forming from gas stripped from satellites dominates in all cases. In the next section we discuss each category in more detail and compare their properties.

4.1 Heated disc stars

The central galaxies in our three simulations undergo several episodes of disc destruction and regrowth at $z > 3$. Over the redshift range $3 > z > 2$, a stable disc is established. This disc continues to grow until $z = 0$, although its angular momentum axis may precess. Our heated disc category only includes stars that once belonged to this stable disc. Stars on highly circular orbits may be scattered to more eccentric orbits by secular evolution and satellite impacts (e.g. Purcell et al. 2010). We refer to this loosely as ‘heating’, in the sense of an increase in non-circular motion. These perturbed disc stars are likely to have a clear kinematic and chemical relationship to those in the present-day thin disc.

We identify all star particles in the $z = 0$ disc, as defined in Section 3, that exist in a given earlier snapshot and use these to define $J_z$ (assuming that the number of star particles scattered into the disc is negligible). We then apply the circularity threshold $\mathcal{E}_E > 0.8$ to identify all newly formed
star particles in the disc at that snapshot. Any of these that have $E_E < 0.8$ at $z = 0$ are assigned to our heated disc category.

Beyond a certain redshift, $z_{\text{form}}$, we can no longer reliably identify a stable progenitor of the $z = 0$ disc, and hence we cannot define $J$. This limit is due to the small number of star particles in the disc at that snapshot. Any of these that have $E_E < 0.8$ at $z = 0$ are assigned to our heated disc category.

Table 4 gives $z_{\text{form}}$ for each of our simulations, along with $z_{1/2}$, the redshift by which the $z = 0$ disc has assembled half its final mass. Table 4 also gives $f_{\text{form}}$, the mass fraction of $z = 0$ disc stars that form earlier than $z_{\text{form}}$. This fraction is no more than 16 per cent (Aq-E). Stars scattered from this unidentified protodisc (and any others that were completely destroyed before $z_{\text{form}}$) are considered to fall into one of the other two in situ categories, according to the origin of their parent gas particle.

### 4.2 Stars from stripped gas and smoothly accreted gas

Halo stars can form directly in the circumgalactic medium, either in quasi-free-falling cold gas clouds (not associated with dark matter clumps) or the gaseous tidal or ram pressure stripped streams of satellite galaxies. We distinguish between these two possibilities based on whether or not the parent gas particle of a given star particle was bound to another dark matter halo before being bound to the main halo. Stars forming from stripped satellite gas particles may be chemically and kinematically similar to stars in the accreted stellar halo. In contrast, stars forming in gas condensing out of the hot hydrostatic gas halo, or other ‘smoothly’ accreted cold clumps, may have properties more similar to those expected of an in situ halo formed by monolithic collapse.

Fig. 3 shows the absolute star formation rate of each in situ category as a function of time elapsed since the Big Bang. These star formation rates are low compared to those typical of the stable disc and the progenitors of accreted stars ($\sim 1 \, M_\odot \, \text{yr}^{-1}$). The majority of halo stars that form in stripped or smoothly accreted gas are more than 9 Gyr old, only marginally younger than the typical age of accreted stars. In Aq-D and Aq-E, there are also 2 Gyr-long bursts of in situ star formation at lookback times of $\sim 6$ and 5 Gyr respectively. Interestingly, these also correspond to episodes of formation for scattered disc stars (blue) and thin disc stars (not shown). This may be due to the rapid infall of cold gas onto the disc during massive merger events.

Another notable feature of Fig. 3 is that the star formation rate in smoothly accreted gas (red) is clearly correlated with that in stripped gas (green), especially in the dominant early epoch of in situ halo formation (ages $> 9$ Gyr). This correlation persists even if we select only stars forming at $r > 30$ kpc, far away from the disc, suggesting that the conditions under which most in situ halo stars form are in
fact related to the accretion and stripping of gas-rich satellites. It appears that star formation may be triggered by the mixing of free-floating gas from the hydrostatic halo with star-forming stripped gas. We also see corresponding peaks in the accreted halo star formation rate, suggesting that star formation is triggered in the infalling satellites as well.

5 IN SITU HALOES AT $z = 0$

In this section, we examine the observable characteristics of in situ halo stars at the present day, starting with a summary of halo properties and then looking in more detail at regions analogous to the Solar Neighbourhood.

5.1 Whole halo

Fig. 4 compares the spherically averaged density profiles of our three in situ halo categories and accreted halo stars. In the $r < 20$ kpc region where in situ halo stars dominate over accreted stars, they contribute roughly equal mass fractions; the exact proportions vary from halo to halo. We see a strong correspondence between stars formed from stripped and smoothly accreted gas at all radii, which, in combination with Fig. 3, suggests that they form with a similar distribution in both space and time. As expected, heated disc stars have a higher profile, with most concentrated at $r < 20$ kpc.

Fig. 5 shows Toomre diagrams (Sandage & Fouts 1987) that compare the amplitude of circular and radial motion for different components. A galactocentric UVW velocity frame (e.g. Binney & Merrifield 1998, p. 627) is defined with respect to the thin disc in each simulation.

Of the three simulations, the stellar halo in Aq-C has kinematic properties most similar to those measured for the Milky Way. The peak rotational velocity of the disc is $\sim 220$ km s$^{-1}$. The heated disc stars (blue) rotate in the same sense as those on circular orbits, with a lag of $\sim 40$ to $180$ km s$^{-1}$. Stars formed from stripped and smoothly accreted gas are kinematically indistinguishable from each other, once again pointing to a close correlation between the dynamics of the two components. In the Toomre diagram they resemble the classical Milky Way halo, with zero net rotation and high radial velocity dispersion. Accreted halo stars show a similar distribution overall, but with notable overdensities due to individual streams, some of which have a net retrograde motion.

The heated disc stars in Aq-D and Aq-E have similar kinematics to those in Aq-C, but the stripped/smooth in situ haloes have a greater net rotation. In Aq-E, all three components once again resemble one another, although the stripped and smooth-gas halo stars have a greater velocity dispersion. An underlying stripped/smooth in situ halo may still be present, but the bulk of in situ halo stars are more similar kinematically to the Milky Way thick disc. The behaviour of accreted stars once again resembles that of the in situ component, even to the extent that they have a strong prograde rotation in Aq-E. Accreted halo components with prograde rotation were noted by Abadi et al. (2003) and also found in Milky Way-like systems in the GIMIC simulations (Font et al. 2011; McCarthy et al. 2012).

Finally, in Fig. 6, we examine the normalized metallicity distribution functions (MDFs) of each component of the in situ halo. Heated disc stars have the highest median [Fe/H] and narrowest dispersion. Their MDF resembles that of the thin disc, but is slightly more metal poor (by $\sim 0.5$ dex in Aq-C). Both in situ and accreted halo stars are systematically more metal poor than heated disc stars.

The MDF of in situ halo stars formed from stripped gas is very similar to that of accreted satellite stars, with a median systematically higher by no more than 0.1 dex. This is
to be expected, as the dense cold gas stripped from satellites will have been enriched by the same stellar populations that make up the accreted halo. Moreover, very similar distributions will also result if prolonged star formation occurs in satellite galaxies while their gas is being stripped. The overall in situ MDF is close to that of the stripped-gas stars, since they dominate the in situ mass budget.

Looking in detail, the degree of similarity between the MDFs of the various components varies in each of our three simulations. This may depend on the extent to which the satellite galaxies contributing the bulk of stripped-gas stars are the same as those that contribute the majority of accreted stars. In practice, because gas can be more easily expelled from shallower potentials, the most massive and metal-rich accreted progenitor galaxies are likely to retain the most gas when they enter the main dark matter halo. Stars stripped from these galaxies are expected to dominate the accreted halo, particularly near the centre.

Of the different in situ components, it is the stars that formed from smoothly accreted gas that have the lowest median metallicity and the broadest dispersion. This is consistent with the expectation that the gas surrounding each galaxy will be a mix of its own metal-rich ejecta and a large quantity of ‘pristine’, or only marginally enriched, gas from direct cosmological infall (Crain et al. 2010). In our simula-

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**Figure 4.** Spherically averaged density profiles of halo stars in the accreted and three in situ components for Aq-C (top), Aq-D (centre) and Aq-E (bottom).

**Figure 5.** Toomre diagrams of the whole stellar halo. For stripped-gas, smooth-gas and heated disc in situ halo stars (red, green and dark blue respectively), contours mark the regions enclosing 10%, 30%, 50%, 70% and 90% of the stellar mass. For the accreted halo (cyan) only 10%, 50% and 90% levels are shown. The dashed vertical line marks the rotation velocity of the disc at 8 kpc.
Figure 6. [Fe/H] distributions for the disc, accreted halo and three in situ halo components. Distributions are normalized by the total mass of stars in each component.

Figure 7. Metallicity distribution functions, as Fig. 6, but here in the Solar Neighbourhood.

5.2 The Solar Neighbourhood

As a rough analogue of the Solar Neighbourhood region most relevant to current observations, we examine the average properties of halo stars in a torus of cross-sectional diameter 4 kpc and galactocentric radius \( r = 8 \) kpc in the plane of the thin disc.

Table 5 summarizes the fraction of stars in each component. For a more direct comparison to the real data, we have grouped heated disc stars and stars that meet our thin disc circularity cut into a single disc component, because the typ-

ically high circular velocities of heated disk stars would most likely result in them being classified as ‘thick disk’ rather than halo stars in observations. Approximately 10 per cent of the stellar mass then remains in a component resembling the ‘classic’ halo, of which accreted stars contribute between 34 and 67 per cent.

Toomre diagrams in this region are almost identical to those in Fig. 5. The biggest differences in comparison to the overall halo are found in the Solar Neighbourhood MDFs, which are shown in Fig. 7. Stars formed from smoothly accreted gas that end up in the Solar Neighbourhood are more metal rich on average, such that their MDF has a very similar shape and amplitude to the accreted halo. This may be because the metal-poor contribution of this component seen in Fig. 6 is dominated by stars forming at large radii from
gas that has not been polluted by the galactic wind of the central galaxy. Other components have the same relationship to one another as those in Fig. 6. Hence, we find no substantial differences between the properties of the in situ halo in the Solar Neighbourhood and the in situ halo overall. This is not surprising because we have already seen that the bulk of the in situ halo is concentrated within r ≲ 20 kpc.

6 Satellite Progenitors
We have shown that our simulated stellar haloes are dominated by satellite accretion: the bulk of halo stars are stripped directly from satellites, and the majority of ‘in situ’ halo stars form from gas stripped from satellites. However, as Fig. 2 demonstrates, stars formed in situ from stripped gas have a more centrally concentrated spatial distribution at z = 0 than directly accreted stars. In this section we examine the satellites which contribute to the halo, with the aim of determining how their infall times, masses and baryonic content affect the spatial distribution of the in situ and accreted components.

We first ask whether the subset of satellite progenitors contributing the gas from which an in situ stellar halo forms are the same subset contributing accreted stars. Fig. 8 compares the mass fractions of stars formed from stripped gas and directly accreted stars associated with each progenitor satellite. In all three simulations, satellites that contribute significantly to one component also tend to contribute significantly to the other. There is substantial variation in detail between the three haloes, reflecting their different accretion histories. A larger scatter is apparent in Aq-D, as well as a noticeable fraction of gas-poor contributors (lower-right area of the plot) relative to Aq-C and Aq-E. A larger fraction of those satellites also survive to z = 0 without being disrupted (blue points). The smaller number of surviving satellites in Aq-C reflects a quieter recent merger history.

In Fig. 9 we isolate the top three satellite progenitors of the stripped-gas in situ component and plot the density profiles of the accreted and stripped-gas stars they contribute. Aq-E stands out as having the most similar profiles for the two components, both of which are slightly steeper than the total accreted profile. In this case, the satellites plotted account for around 40 per cent of the total stripped-gas halo. With the possible exception of accreted stars in Aq-C, both accreted and stripped-gas stars from the top three satellites are distributed like the bulk of the stellar halo.

Fig. 9 suggests that the greater central concentration of the stripped-gas halo profile is not simply because most of the progenitor gas particles originate in more massive progenitors, which sink more rapidly though the action of dynamical friction. If that were the case, we might also expect stars accreted from the same progenitors to be more centrally concentrated than the accreted halo overall. Instead, we see that the debris profiles of the three most massive individual progenitors are very similar to the profile of the entire accreted halo. In our simulations, at the present day, accreted stars are distributed (on average) over the same range of radii at which they were liberated from their parent satellites. Conversely, we have confirmed that the stripped gas particles from which in situ halo stars form dissipate some of their orbital energy between the times of stripping and star formation. The present-day distribution of the stripped gas halo is therefore imprinted at the time those stars form, rather than the time at which their parent gas particles are stripped.

7 Discussion
Our finding of accretion-triggered star formation in smoothly accreted gas may be, at least in part, a consequence of our hydrodynamics scheme. In some hydrodynamic models, cold clouds can condense independently of tidally stripped gas, while in others, condensation and mixing by fluid instabilities may both be suppressed. It is clearly important to know what fraction of stars are formed as a result of implementation- and resolution-dependent effects, before any definitive conclusions about in situ stellar haloes can be drawn. This uncertainty is currently the limiting factor for in situ stellar halo predictions based on hydrodynamic simulations. There are no strong observational constraints on the behaviour of different models at this level of detail. The comparison of simulations from different groups will be extremely useful in this regard, hence our emphasis on simple definitions for the different halo components.

Given this uncertainty, it is worth noting that, with a single SPH code, the different cosmological initial conditions of our three simulations result in markedly different in situ halo properties at z = 0. It is obvious that the mass spectrum, arrival time distribution and prior star formation histories of accreted satellites directly determine the properties of the accreted halo. Remarkably, however, in our SPH simulations, these factors are also extremely important in the formation of the in situ halo. Without satellite accretion, there would be hardly any in situ halo stars in our simulations. Moreover, it is unlikely that all the stars we classify as heated disc halo stars would be considered as such by observers. The vast majority are on orbits of moderate circular velocity corotating and coplanar with the thin disc.

### Table 5. Breakdown of all stars in the Solar Neighbourhood. Heated disc stars are grouped together with thin disc stars in this table. The top two rows give fractions of total stellar mass, while the lower three rows give fractions of stellar halo mass (second row) only.

| Mass [10^8 M_☉] | Aq-C | Aq-D | Aq-E |
|-----------------|------|------|------|
| Disc stars (Thin + Thick) | 26.4 (92.3%) | 27.4 (88.7%) | 28.0 (83.0%) |
| Halo stars | 2.21 (7.7%) | 3.49 (11.3%) | 5.72 (17.0%) |
| Accreted | 0.747 (33.9%) | 1.79 (51.1%) | 3.83 (67.0%) |
| Stripped gas | 0.837 (37.9%) | 1.23 (35.3%) | 1.53 (26.7%) |
| Smoothly accreted gas | 0.618 (28.0%) | 0.476 (13.6%) | 0.356 (6.23%) |
and would likely be classified as ‘thick disc’ stars as discussed in Section 3. In Aq-C, a large fraction of these stars belong to the end of a bar in the galactic plane that extends slightly beyond our ‘bulge’ cut at 5 kpc.

Our model is clearly not unique. Nonetheless, our in situ haloes are compatible with the basic observable properties of the Milky Way’s stellar halo, if we exclude scattered disc stars. Stars formed from stripped and smoothly accreted gas in the main halo are old and metal poor, with a significant tail to low metallicity. The kinematic and chemical similarities are closest in Aq-C, which also has the most Milky Way-like thin disc.

Two of our haloes conform to the expectation from earlier work that in situ halo stars are more concentrated than accreted stars, but in the third, the in situ and accreted halo density profiles are almost identical. Interestingly, it is only in this third case that there is a significant difference in the metallicity distribution functions of in situ and accreted stars.

Figure 8. Mass fraction of the accreted halo and stripped-gas halo contributed by disrupted (red) and surviving (blue) satellite galaxies. The sizes of the points are proportional to the logarithm of the satellite’s total mass at infall, as shown by the legend in the first panel. The diagonal dashed line indicates an equal fractional contribution to the accreted and stripped-gas components.

Figure 9. Spherically averaged density profiles of halo stars associated with the top 3 contributors to the ‘stripped-gas’ component. The profiles of stars formed from gas contributed by those galaxies are shown as dashed, cyan lines, while the profile of stars accreted from those satellites directly are shown as solid, green lines. Thinner, black lines of the same styles show the corresponding total profiles.
McCarthy et al. (2012) studied the origin of in situ halo stars in 412 Milky Way-mass galaxies from the GIMIC simulations, which have a dark matter particle mass \( \sim 300 \) times larger than our simulations. With the same definition of disc stars and accreted stars, they find in situ halo mass fractions ranging from 20 to 60 per cent. Their in situ stars are, on average, younger and more metal rich than their accreted halo stars, with a centrally concentrated oblate distribution and prograde rotation. They demonstrate that these properties result from star formation at \( z \sim 1 \) in ‘proto-discs’ that are subsequently destroyed.

Although our three simulations produce total in situ mass fractions consistent with the distribution found by McCarthy et al. (2012), there are some notable differences in the origin of in situ stars. Accreted gas is the dominant contributor to our in situ haloes, whereas McCarthy et al. find approximately half of their in situ halo mass is formed from gas that is shock-heated to the virial temperature of the main dark matter halo. Our in situ dark matter haloes form at somewhat higher redshift and we can trace back our \( z = 0 \) discs to \( z \sim 2.5 \), supporting the suggestion of McCarthy et al. that the Aquarius simulations have quieter-than-average accretion histories. As McCarthy et al. do not compute the fraction of gas forming their in situ component that was previously bound to satellites, it is likely that their proto-disc stars mix together both stripped and smoothly accreted gas, and possibly some fraction of our heated disc population. Font et al. (2011) note that formation from stripped gas is apparent in the same set of galaxies from the GIMIC simulations and is likely responsible for their in situ stars at \( r > 20 \) kpc. We find that this mode of formation dominates at somewhat smaller radii. This may be a consequence of the better spatial resolution in our simulations; a smaller gravitational softening length means satellite gas tends to be more tightly bound, allowing it to sink further into the potential before being stripped by ram pressure or tidal forces (see also Parry et al. 2012).

Tissera et al. (2012, 2013, 2014) examine in situ halo stars in six SPH simulations from the Aquila suite. They also use GADGET-3, but with different implementations of subgrid physics and slightly lower resolution (a factor of 5 in DM particle mass; Scannapieco et al. 2012). Two of their simulations, Aq-C and Aq-D, have the same initial conditions as the simulations with the corresponding labels in this paper. To aid the reader in comparing our results with this series of papers, we comment here on the differences between our sample definitions and those of Tissera et al.

Tissera et al. separated disc and halo stars with a circularity cut, \( J_z/J_{\text{circ}}(E) > 0.65 \), which classifies many more stars as ‘disc’ than our cut. Also, they did not restrict the height of disc stars above the midplane. They excluded bulge stars with an energy criterion that roughly equates to a radius of 5 kpc, comparable to our bulge cut (Tissera et al. 2012).

In the analysis of Tissera et al., in situ halo stars are divided into ‘inner’ (more bound) and ‘outer’ (less bound) populations according to a cut in relative binding energy. This equates to a radial cut in the range \( 14 < r < 36 \) kpc (15 and 19 kpc for Aq-C and Aq-D respectively). They further subdivided these populations by origin, according to whether the stars were formed outside the virial radius (‘debris’) or inside (‘endo-debris’). This definition is different to ours, which counts a present-day halo star particle as ‘accreted’ if it formed bound to a satellite subhalo, regardless of whether the satellite was inside or outside the virial radius of the main dark matter halo at the time. This may not be significant, because the fraction of accreted halo stars formed in bound satellites after their infall is typically small (see McCarthy et al. 2012).

The definition of heated disc halo stars in Tissera et al. only requires the star particle to have \( J_z/J_{\text{circ}}(E) > 0.65 \) at its formation. Our definition also requires those stars to have been scattered from the disc that survives at \( z = 0 \); we would classify some fraction of their heated disc stars as formed from either stripped or smoothly accreted gas. This may explain why Tissera et al. find a much larger heated disc fraction in Aq-C despite their less stringent disc circularity cut (indeed, they note that heated disc stars have retrograde rotation in one of their simulations). Most heated disc stars in Tissera et al. have \( \mathcal{E}_K > 0.5 \), as in Fig. 1.

The selection criteria used by Tissera et al. make it difficult to compare their results to ours directly. A number of similarities are clear, however. They find an approximately equal ratio of in situ to accreted stars for their ‘inner halo’ populations, which agrees with our results for the region \( 5 < r < 20 \) kpc. Moreover, they also find that scattered disc stars make a negligible contribution outside this region. The kinematic properties shown in our Fig. 5 are similar. In Aq-C and Aq-D, the median [Fe/H] of endo-debris stars is lower than those of debris stars by 0.17 dex and 0.26 dex respectively. This is the opposite of what we find, but could be easily explained if the Tissera et al. endo-debris definition includes a similar or larger fraction of stars formed from smoothly accreted gas.

8 CONCLUSIONS

We observe the following properties of in situ stellar halo stars in three high resolution SPH simulations of Milky Way analogues:

(i) The in situ stellar halo accounts for \( 30 - 40 \) per cent of the stellar mass outside the thin disc and bulge. This fraction includes stars that observers may classify as belonging to a thick disc.

(ii) The in situ halo dominates over the accreted stellar halo at \( r < 30 \) kpc in 2 out of our 3 simulations. In the third simulation, both in situ and accreted halo stars have almost the same volume density distribution.

(iii) Between 2 and 30 per cent of the in situ halo comprises stars scattered from near-circular orbits in the plane of the thin disc to more eccentric orbits. These form at lookback times of 5 to 9 Gyr, retain high circular velocities and have relatively narrow metallicity distribution functions (MDFs) with median \( -1 < [\text{Fe/H}] < -0.5 \). This component resembles the Milky Way’s thick disc, although we note that, in 2 out of our 3 simulations, kinematically selected eccentric/thick discs also have a significant contribution from both accreted stars and stars formed from accreted gas.

(iv) The rest of the in situ halo stars form in gas clouds in the circumgalactic halo, on highly eccentric orbits near the disc plane, or in the chaotic gas-rich stage of the galaxy’s formation (\( z > 2.5 \)), before a stable disc is established. In
one simulation, these halo stars strongly resemble the ‘classical’ isotropic, metal-poor, dispersion-supported stellar halo of the Milky Way. In the other two simulations, most halo such stars have significant rotation in the same sense as the thin disc.

(v) We identify two distinct origins for these stars: gas that has been stripped out of satellite galaxies by tides and ram pressure, and gas that is incorporated directly into the ‘smooth’ halo of the main galaxy by cosmological infall and supernova-driven outflow from the central galaxy.

(vi) Stars formed in situ from stripped gas have a very similar MDF to the accreted stellar halo, because this gas is brought in by the same progenitor satellites. Halo stars formed from smoothly accreted gas have a broader MDF and are, on average, the most metal poor of the components we identify.

(vii) The density profile of halo stars formed in situ from stripped gas is more concentrated than that of the stars accreted from the same progenitor galaxies. This reflects dissipative collapse of this stripped gas after it is liberated, rather than differences in how and when star and gas particles are stripped, or in the contributions of different satellites.

(viii) In all cases, among the in situ halo stars not scattered from the disc, there is almost no difference in the present-day phase-space distribution of those formed in stripped and smoothly accreted gas. The correspondence is so close that we suggest that, in our simulations, star formation in the hot gaseous halo is directly triggered by the passage of dense clumps of star-forming stripped gas.

(ix) The properties of in situ stars in the Solar Neighbourhood are representative of the in situ halo overall, except that stars formed from smoothly accreted gas in this region are notably more metal rich. Based on these findings, we conclude that essentially all halo stars in our simulation are the result of cosmological accretion and merging, with no obvious bimodality due to an in situ halo forming through a quasi-monolithic collapse of enriched diffuse gas.

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