Chapter 1
Stellar Tidal Streams in External Galaxies

Jeffrey L. Carlin, Rachael L. Beaton, David Martínez-Delgado, and R. Jay Gabany

Abstract  In order to place the highly substructured stellar halos of the Milky Way and M31 in a larger context of hierarchical galaxy formation, it is necessary to understand the prevalence and properties of tidal substructure around external galaxies. This chapter details the current state of our observational knowledge of streams in galaxies in and beyond the Local Group, which are studied both in resolved stellar populations and in integrated light. Modeling of individual streams in extragalactic systems is hampered by our inability to obtain resolved stellar kinematics in the streams, though many streams contain alternate luminous kinematic tracers, such as globular clusters or planetary nebulae. We compare the observed structures to the predictions of models of galactic halo formation, which provide insight in the number and properties of streams expected around Milky Way like galaxies. More specifically, we discuss the inferences that can be made about stream progenitors based only on observed morphologies. We expand our discussion to consider hierarchical accretion at lower mass scales, in particular the observational evidence that substructure exists on smaller mass scales and the effects accretion events may have on the evolution of dwarf galaxies (satellite or isolated). Lastly, we discuss potential correlations between the presence of substructure in the halo and the structural properties of the disk. While many exciting discoveries have been made of tidal substructures around external galaxies, the “global” questions of galaxy formation and evolution via hierarchical accretion await a more complete census of the low surface brightness outskirts of galaxies in and beyond the Local Group.
1.1 Introduction

Low surface brightness features, including “tails” and “bridges,” are visible in highly disturbed galaxies that result from a major merger or strong encounter (Arp, 1966; Toomre & Toomre, 1972). Similarly, diffuse stellar streams and shells around massive elliptical galaxies have been known for decades, and are attributed either to the accretion of smaller disk galaxies (Quinn, 1984) or to recent, “in-situ” star formation from gas that was already contained within the galaxy (Fabian et al., 1980). Schweizer & Seitzer (1988) extended these observations to early spiral galaxies, and suggested that the “ripples,” as they called the shell-like features, were formed through mass transfer from nearby galaxies, in addition to wholesale mergers.

It has only been in recent years, with the advent of wide-area, deep photometric surveys, that the number and variety of stellar substructures (resulting from the tidal disruption of dwarf galaxies and globular clusters in “minor mergers”) threading the halos of the Milky Way and Andromeda (M31) galaxies has become apparent. These stellar substructures can be studied in detail and together describe the hierarchical merging history of the two dominant galaxies in the Local Group. However, placing them in the broader context of cosmological galaxy formation models requires a more general picture of halo substructure only feasible via the exploration of a large number of more distant systems. Only with such a dataset in hand is it possible to determine whether the Milky Way and M31 have experienced ‘typical’ or ‘atypical’ merging histories (e.g., Mutch et al., 2011).

Models (e.g., Johnston et al., 2008; Cooper et al., 2010) predict that a survey reaching a surface brightness of \( \sim 29 \) mag arcsec\(^{-2} \) around \( \sim 100 \) galaxies outside the Local Group should reveal many tidal features, perhaps as much as one detectable stream per galaxy. However, a suitably deep data set that is sensitive to low surface brightness features in a large number of galaxies does not yet exist, leaving the observational evidence needed to test these predictions incomplete. In the sections that follow, we will discuss the isolated discoveries of tidal debris structures in external galaxies and their overall utility for elucidating general stellar tidal features.

1.2 Stellar streams: detection methods and examples

Local Group galaxies, including the Milky Way and M31, can be dissected star by star, and thus provide a laboratory for understanding the details of hierarchical galaxy formation. However, it is unclear whether the Local Group galaxies represent typical evolution histories. To understand the place of the Milky Way and M31 in the larger context requires studying tidal substructures in galaxies beyond the Local Group, where resolving individual stars is difficult. In this section, we detail some of the methods used to discover tidal debris features, including resolved and unresolved stellar populations, and discuss the unique insights gleaned from some examples of these structures.
1.2.1 Resolved stellar structures in the Local Group

The era of massive, deep photometric surveys has enabled the detection of tidal debris structures within the Milky Way as stellar overdensities of carefully selected tracers. The famous “Field of Streams” image from SDSS (Belokurov et al. 2006; reproduced in Chapter 1) mapped substructure using main sequence turnoff (MSTO) starcounts to surface brightness limits of fainter than \( \sim 32 \) mag arcsec\(^{-2}\). The identification of individual members of stellar streams enables extremely low surface brightness features to be detected. This can be achieved by kinematical selection of stream members (for example, via spectroscopic velocities), allowing features in the Galactic halo containing fewer than \( \sim 1 \) red giant branch (RGB) star per square degree to be identified.

Likewise, in M 31, photometric selection of metal-poor RGB candidates removes much of the contaminating background, and has allowed detections of features as faint as \( \sim 30 \) mag arcsec\(^{-2}\), including the “giant stream” (Ibata et al. 2001) and other low surface brightness features (e.g., Ferguson et al. 2002; see Chapter 8 for more about M31). When individual stars can be resolved and spectroscopically vetted in M 31, the measurement of surface brightnesses as faint as \( \sim 32 \) mag arcsec\(^{-2}\) is possible (see, e.g., Gilbert et al. 2012 and other results from the SPLASH survey). Thus, we are able to probe both the Milky Way and M 31 to depths of \( \sim 32 \) mag arcsec\(^{-2}\), which is deep enough to sample most of the simulated halo substructures seen in simulations (discussed further in Section 1.4).

1.2.2 Detection methods in and beyond the Local Group

Current ground-based telescopes are unable to resolve stellar tidal streams around most galaxies beyond the Local Group into individual stars. Most of the streams that have been found in external galaxies thus appear as elongated, diffuse-light regions extending over several arcminutes on the sky. To map such tidal streams requires deep imaging that is also sensitive to extremely faint surface brightness features; the typical surface brightness of known stellar tidal streams is 27 mag arcsec\(^{-2}\) or fainter, depending both on the luminosity of the progenitor and the time they were accreted (Johnston et al. 2008).

Faint tidal features can be identified on sky-limited archival photographic plates using a process called photographic amplification; the surface brightness limit is even fainter if photographically amplified derivatives of several plates are combined together (Malin 1981). Using these techniques (photographically or digitally) it is possible to detect extended features to 28 mag arcsec\(^{-2}\) from existing photographic surveys (Malin & Hadley 1997). This depth is comparable to that achievable with SDSS in Figure 1.1.

Small, fast (i.e., low focal-ratio) telescopes (e.g., Martínez-Delgado et al. 2010; van Dokkum et al. 2014) and modern CCD cameras are capable of imaging unresolved structures in external galaxies to \( \Sigma_r \sim 29 \) mag arcsec\(^{-2}\). Detecting these
faint features requires very dark sky conditions and images taken with exquisite flat-field quality over a relatively large angular scale. More specifically, stellar streams are typical found at large galactocentric distances ($15 \text{kpc} < R < 100 \text{kpc}$, or farther) and could be found out to a significant portion of the virial radius of the parent galaxy (for the Milky Way or M 31, $R_{\text{virial}} \sim 300 \text{kpc}$). Thus, surveys for stellar debris must produce images over large angular scales (from $> 30'$ for systems < 10 Mpc to $\sim 15'$ for systems $\sim 50$ Mpc away). As an example, the survey strategy employed by Martínez-Delgado et al. (2010) uses stacks of multiple deep exposures of each target taken with high throughput clear “luminance” filters (transmitting $4000 \text{Å} < \lambda < 7000 \text{Å}$ with a near-IR cut-off) with typical exposure times of 7-8 hours.

Recent deep, wide-field imaging surveys have focused on nearby spiral galaxies that were suspected (based on existing data from, e.g., surveys such as POSS-II or SDSS, or from amateur astronomical imaging) to contain diffuse-light over-

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**Fig. 1.1** Left panels: images from the Sloan Digital Sky Survey of the nearby galaxies NGC 4013 (top) and M 63 (bottom). These images do not show any obvious signs of tidal streams in the halos of these galaxies at the surface brightness limit of SDSS. Deep images of these same galaxies reveal a low-latitude stellar stream around NGC 4013 (upper right panel; Martínez-Delgado et al. 2009) and a giant tidal stream around the spiral galaxy M 63 (lower-right; Chonis et al. 2011). For reference, a color inset of each galaxy’s central regions has been inserted atop the deeper images. These images illustrate the value of deep, sensitive imaging (i.e., beyond that of SDSS) for detecting the faint debris structures predicted by theoretical models in external galaxies.
Fig. 1.2 Luminance filter images of nearby galaxies from the pilot survey of Martínez-Delgado et al. (2008, 2010) showing large, diffuse light structures in their outskirts. These include tidal streams similar to Sagittarius (upper right panel), giant plumes (middle panels in the top row), partially disrupted satellites (top row, third panel from left), umbrella-shaped tidal debris structures (middle two panels in the bottom row), enormous stellar clouds, prominent spikes, and large scale, complex inner halos sprinkled with several debris features. A color inset of the disk of each galaxy has been overplotted for reference. An illustrative comparison of these features to the surviving structures visible in cosmological simulations is given in Martínez-Delgado et al. 2010, their Fig 2.

To date, the combined observational efforts have revealed more than 50 previously undetected stellar structures in galaxies as distant as 80 Mpc. Figure 1.2 shows eight such galaxies from the survey of Martínez-Delgado et al. (2010), illustrating the variety of tidal debris features – both in their morphologies and in their projected radii. The central disks of the galaxies shown in Figure 1.2 are of similar overall physical size, but the debris features can span large galactocentric distances. The morphologies of the features include great circle streams resembling the Sagittarius stream around our Galaxy (upper right panel of Figure 1.2), Sagittarius is discussed in Chapter 2 of this volume), isolated shells, giant clouds of debris floating within galactic halos, jet-like features emerging from galactic disks, and large-scale diffuse structures that may be related to the remnants of ancient, already thoroughly disrupted satellites. The diversity in observed substructure morphology parallels that seen in simulations (e.g., Johnston et al. 2008 Cooper et al.)
In addition to the remains of satellites that are likely completely destroyed, there are a few examples (e.g., Martínez-Delgado et al. 2012, 2014, Amorisco et al. 2015) of surviving satellites caught in the act of tidal disruption, displaying long tails departing from the progenitor satellite (i.e., similar in spirit to observations in the Local Group). The extraordinary variety of morphological specimens provides strong evidence to support the hierarchical galaxy formation scenarios predicted by cosmological models (e.g., Cooper et al. 2010).

1.2.3 Unresolved features beyond the Local Group

Prior to recent dedicated CCD searches, only a few cases of extragalactic stellar tidal streams have been reported in nearby spiral galaxies. Malin & Hadley (1997) found two possible tidal streams surrounding the galaxies M83 and M104 by using special contrast enhancement techniques on plates obtained for wide-field photographic surveys. Shortly thereafter, a study of the nearby, edge-on galaxy NGC 5907 by Shang et al. (1998) employed deep CCD images to reveal an elliptical loop in the halo of this galaxy, which they believed to be the remains of a tidally disrupted galaxy similar in size to the Sagittarius dwarf galaxy (Sagittarius was at that time a recent discovery in the Milky Way halo). Shang et al. also identified another Sagittarius-like dwarf galaxy that they suggested might be interacting with the disk of NGC 5907, causing the observed warp in HI. Their photometry reached surface brightnesses of 28.6 and 26.9 mag arcsec$^{-2}$ in R and I-bands, respectively.

More recently, NGC 5907 was imaged by Martínez-Delgado et al. (2008, Figure 1.3), revealing even fainter features of the stream. As shown in Figure 1.3, this stream is prominently visible as an interwoven, rosette-like structure traversing nearly 720° around NGC 5907. Detailed N-body modeling suggests that all of the features can be reproduced from the accretion of a single, low-mass satellite galaxy, with the stream tracing two full orbits of its progenitor. The presence of such a long stream confirms that a stellar substructure can survive several gigayears, which though predicted by N-body simulations of tidally disrupted stellar systems around the Milky Way (e.g., Law et al. 2005, Peñarrubia et al. 2005) lacked direct confirmation. Interestingly, the N-body model of Figure 1.3 was created using a progenitor with orbital parameters similar those found for Sagittarius in the Milky Way (Chapter 2). The model suggests that the fainter, outer loop material (blue points in Figure 1.3) became unbound from its progenitor at least 3.6 Gyr ago. The substructure in NGC 5097 is one of the most striking examples of an external great-circle tidal stream to date.

While some galaxies have great-circle tidal streams that resemble the Sagittarius stream surrounding our Galaxy (e.g., in NGC 5097: Figure 1.3, or NGC 4013 and M63: Figure 1.1), others have enormous structures that resemble open umbrellas, and that extend over tens of kiloparsecs (e.g., the middle two panels in the bottom row of Figure 1.2). These structures are often located on both sides of the host galaxy, and display long narrow shafts that terminate in a giant shell of debris (e.g.,
Fig. 1.3 Left: deep image of the stellar tidal stream around NGC 5907 obtained with the 0.5-meter BBO telescope (Martínez-Delgado et al., 2008). The great-circle morphology of this system is likely very similar to that of the Sagittarius stream in the Milky Way. Right: N-body model of the NGC 5907 stellar stream. The satellite is realized as a King model with an initial mass, King core and tidal radii of $M = 2 \times 10^9 M_\odot$, $r_c = 0.39$ kpc and $r_t = 2.7$ kpc, respectively. Different colors denote particles that became unbound after different pericentric passages, whereas black particles are those that remain bound. The fainter, outer loop material (blue points) became unbound at least 3.6 Gyrs ago. For this particular model the orbital period is $T_r = 0.9$ Gyr.

NGC 4651: [Foster et al., 2014]. Another umbrella-like feature, dubbed the “dog leg stream” (Amorisco et al., 2015), has a long narrow spoke (with an embedded progenitor) that stretches to a radius of ~150 kpc beyond the center of NGC 1097, terminating in a “dog-leg” that appears like an umbrella feature with one half of the shell missing (note that this system has other narrow plumes visible as well). With such examples, we are beginning to see real streams around galaxies in the local universe that resemble the menagerie of morphological features predicted by Λ-CDM hierarchical structure formation models (e.g., Johnston et al., 2008; Cooper et al., 2010; see also Chapter 6 of this volume).

While there have been numerous isolated discoveries of debris features around external galaxies, there have been few large-scale systematic surveys to build a comprehensive census of halo substructures. Only such a survey can inform simulations by providing estimates of the prevalence of streams of different morphologies, and thus different progenitor masses, orbits, and infall times. One systematic search
by Miskolczi et al. (2011) analyzed 474 galaxies in SDSS and found clear tidal features around 6% of the galaxies, with 19% exhibiting some features above the surface brightness limit of $\sim 28$ mag arcsec$^{-2}$. From imaging data in the Canada-France-Hawaii Telescope Legacy Survey, Atkinson et al. (2013) find tidal features (including both minor and major merger events) around 12% of the galaxies imaged. Given that the $\Lambda$-CDM paradigm predicts that we should see accretion relics around all Milky Way-sized galaxies, this $\sim 10\%$ fraction from the SDSS/CFHT studies would seem to suggest a significant deficit of detected accretion events relative to predictions. However, as illustrated in Figure 1.1 (see also Figure 1.6), the surface brightness limits for most large scale surveys are simply too shallow to reveal the complex webs of substructure both predicted in simulations (e.g., Bullock & Johnston, 2005) and observed locally in the Milky Way and M 31 (i.e., where $\mu > 28$ mag arcsec$^{-2}$ can be attained using resolved stellar populations). However, it is puzzling that no tidal stream currently known in the Milky Way or M 31 is remotely as bright as the “faint limits” of these large scale searches (Sagittarius – by far the brightest stream in the Milky Way – is only $\sim 30$ mag arcsec$^{-2}$ at about 30-40 deg. from the core, according to Mateo et al. 1998).

1.2.4 Resolved structures beyond the Local Group

With large aperture facilities equipped with wide-field detectors, it is possible to resolve individual stars in some tidal debris structures beyond the Milky Way and M31. Perhaps the most spectacular example of this from ground-based observations is the Milky Way analog NGC 891, at a distance of $\approx 10$ Mpc, which was surveyed by Mouhcine et al. (2010) with Suprime-Cam on the 8.2m Subaru telescope. With very long (>11-hr) exposures, this study resolved stars to $\sim 2$ magnitudes below the RGB tip in NGC 891, covering a $\sim 90 \times 90$ kpc area around the galaxy down to $i$-band magnitudes fainter than 28th mag (see Figure 1.4). Surface density maps of RGB stars show a complex of features looping throughout the halo of NGC 891, suggesting that the halo of this galaxy contains numerous accretion remnants. The disk of NGC 891 also appears to be “super-thick” (Mouhcine et al., 2010), providing further evidence of recent accretion. Another recent example of deep, ground-based observations is the study by Greggio et al. (2014), who mapped the density of RGB stars in the halo of the spiral galaxy NGC 253 at a distance of 3 Mpc using deep Z- and J-band imaging from the VISTA telescope. As a whole, Greggio et al. found that the halo of NGC 253 is fairly homogeneous out to $\sim 50$ kpc, with the exception of a $\sim 20$ kpc wide shell roughly 28 kpc from the plane that is interpreted to be the result of a recent tidal interaction. While these ground-based studies are spectacular, the extremely deep, large-area observations required to resolve individual RGB stars in the accretion relics highlight the difficulty (or perhaps impossibility) of doing similar work for large numbers of Milky Way analogs.

Alternatively, space based telescopes can provide the necessary spatial resolution and depth to trace extra-galactic substructures with individual stars, albeit over
Stellar density map of RGB stars with magnitudes $25.8 \leq i_0 \leq 27.0$ over a $\sim 90 \times 90$ kpc region surrounding the Milky Way analog galaxy NGC 891. Multiple interlocking loops and arc-like (“great circle”) features are visible over vast regions of the NGC 891 halo. [Figure reproduced by permission from Mouhcine et al. (2010).]

significantly smaller angular scales than those on the ground (the HST+ACS field of view is $\sim 4'$). The HST+ACS GHOSTS survey (Radburn-Smith et al., 2011) resolved stars at the RGB tip and used them to map low surface brightness features (to $\Sigma_V \sim 30$ mag arcsec$^{-2}$) in the outer regions of 14 disk galaxies out to distances of $\sim 17$ Mpc. Bailin et al. (2011) began with GHOSTS images from HST for the spiral galaxy NGC 253, and supplemented these with imaging over a much wider field of view with Magellan/IMACS, reaching well below the RGB tip. They estimated the total stellar luminosity of the NGC 253 halo to be roughly twice that of the Milky Way or M31, and fit profiles to stellar densities out to $\sim 30$ kpc from the galaxy center. The shelf-like feature to the south that had been seen by Malin &
1 Hadley(1997) in photographic plates is clearly visible, as well as other substructure at the $\sim$kpc level. Thus, targeted follow-up, ground-based or space-based, for stellar streams discovered in integrated light has the potential to build datasets complementary to those generated en masse for the Milky Way and M 31, reaching appropriate physical spatial scales and surface brightnesses.

1.3 $N$-body modeling of streams

We now turn to discussion of what can be learned from the identification and subsequent theoretical modeling of tidal streams in galaxies beyond the Local Group. In many of the examples illustrated in this chapter, we have shown $N$-body models of disrupting satellites that roughly reproduce the observed morphology of detected streams. For example, for the great-circle tidal stream around NGC 5907 (Figure 1.3), an $N$-body model that best replicates the morphology of the observed stream requires a massive Sgr-like galaxy that has spread debris over at least three orbits. If this is the case, then the complex stream structure seen around this galaxy can be entirely explained by a single accretion event. However, due to the difficulty in measuring kinematics for low surface brightness tidal streams (and, indeed, the impossibility of measuring kinematics of individual stars) at several Mpc away, models must be constrained solely by the observed morphology and the stellar density along the stream. While the panoramic perspective we are afforded of these systems offers many constraints on the properties of the progenitors and their orbits, kinematics will ultimately be needed to fully characterize each accretion event.

It is possible that carefully chosen spectroscopic observations can derive bulk kinematics of some tidal debris features around external galaxies. For example, Sanderson & Helmi (2013) outlined a method to do this for tidal caustics (or “shells”) via careful choice of spectroscopic fiber positioning and identification of the tell-tale velocity signature. A much more promising avenue is to use intrinsically brighter point-like tracers such as globular clusters, planetary nebulae, or HII regions to elucidate debris structures. The densities of globular clusters have been used (D’Abrusco et al., 2015) to show large structures in the halos of Virgo cluster galaxies that may be evidence of recent accretion events.

An example of a stream in a distant galaxy for which kinematics have been measured and an orbit derived is that of the Umbrella Galaxy (NGC 4651). Foster et al. (2014) followed up the low surface-brightness imaging of Martínez-Delgado et al. (2010) with even deeper imaging from the Subaru/Suprime-Cam instrument. Figure 1.5 shows images from this study, which reveal a “stick” feature extending out to its terminus at a broad arc to the left of the main galaxy. On the opposite side of the disk (right side of the upper panel in Figure 1.5), additional shell-like features are clearly seen. Foster et al. (2014) estimated the total stellar mass in the tidal debris to be $\sim 4 \times 10^8 M_\odot$, constituting about 1/50th the stellar mass of NGC 4651. In addition, Foster et al. (2014) obtained spectra of candidate globular clusters, planetary nebulae, and HII regions that are spatially coincident with the substructures,
Fig. 1.5 The stellar stream in NGC4651. Top: color image of the extensive tidal features in NGC4651, including an “umbrella” and several shells of material. The stream has an exceptionally blue color. Bottom left: several globular clusters (yellow circles), planetary nebulae (cyan diamonds), and HII regions (black triangles) are found along the debris. These bright tracers permit kinematical probes that greatly enhance the ability of N-body modeling (bottom right) to elucidate the physical parameters of the accretion event. [Reproduced from Foster et al. (2014).]

and distinguished the kinematical signature of the accreted debris (including a possible progenitor core) from the underlying galactic disk motions. The orbit derived from these is rather radial (as expected for an umbrella-like remnant; see Chapter 6 of this volume), with pericenter of only a few kpc, apocenter of \( \sim 40 \) kpc, and period of \( \sim 350 \) Myr. This implies that the ratio of total mass of the progenitor and the whole of NGC 4651 is \( \sim 0.15 \), making this minor merger event analogous to the Sgr accretion in the Milky Way (see Chapter 2) and the Giant Stellar Stream in M31 (Chapter 8). While detailed exploration of parameter space has yet to be achieved for this system, Foster et al. (2014) did adapt an existing N-body model to show that some inferences can be made from analysis of the surface brightness and velocities of the visible features and associated tracers.

As discussed in Chapter 7, the widths and surface brightnesses of streams that are traced over a long portion of their orbits provide constraints on the number and sizes of dark matter subhalos in the host galaxy’s halo (see, e.g., Ibata et al. 2002, Johnston et al. 2002, Peñarrubia et al. 2006, Siegal-Gaskins & Valluri 2008). These
authors show that the presence of dark matter subhalos in spiral galaxies would result in progressive heating of tidal streams as a result of close encounters, and in fact gaps may be swept out of streams by interactions with subhalos (e.g., Yoon et al. 2011, Carlberg 2013, Erkal & Belokurov 2014, Ngan et al. 2014). As Peñarrubia et al. (2006) pointed out, the average number of dark matter substructures (and, thus, the likelihood of encounters) in a Milky Way-like galaxy decreases monotonically from $z \sim 2$ to the present, implying that “old” stream pieces like the ones visible in external galaxies are more likely to reveal perturbations than recently stripped ones. Tidal debris structures can also be used as kinematical tracers of the underlying gravitational potential in which they are produced (e.g., Johnston et al., 2001; see Chapter 7 for detailed discussion). This has been attempted in the Milky Way using the Sgr streams (e.g., Law et al., 2005, Peñarrubia et al., 2005, Law & Majewski, 2010a; see Chapter 2 of this volume for more discussion of Sagittarius). The use of streams beyond the Local Group may ultimately become fruitful for this purpose, as they can be traced over multiple wraps, providing much stronger constraints on the level of stream precession due to the flattening of the halo. Finally, old stream pieces stretching over multiple orbital wraps allows us to study metallicity gradients in the stream (and thus within the progenitor galaxy), as has been done for the Sgr tidal stream (e.g., Bellazzini et al., 2006, Chou et al., 2007, Chapter 2 of this volume). All of these techniques, and likely many others, applied to external galaxies provide valuable constraints on the hierarchical process of galaxy growth and evolution beyond what can be gleaned from our embedded perspective in the Milky Way.

1.4 Stellar tidal streams as a galactic formation diagnostic

One of the main objectives of stream surveys in nearby spiral galaxies is to compare the observations with cosmological simulations to ascertain whether the frequency and surface brightness of the detected stellar streams are consistent with those predicted by models. Observational modeling and theoretical understanding of such diffuse and intricate features requires specifically tailored cosmological numerical simulations. There are two main difficulties for these models: i) sufficiently fine mass and spatial resolution is needed to recover complex and delicate tidal features around Milky Way mass halos; and ii) a sufficient volume is required to build a statistically meaningful sample of host galaxies. To simultaneously meet these two requirements, state-of-the-art cosmological simulations are needed. For this reason, there are still a limited number of models of the stellar halos of Milky Way-like galaxies. Examples include the models by Bullock & Johnston (2005, also described in Chapter 5 of this volume) and high resolution models of individual stellar halos for Milky Way-like galaxies based on the (dark matter only) Aquarius suite of simulations.

Numerical simulations (e.g., Johnston et al., 2008, Cooper et al., 2010) can be used as a guide to what we may expect; models suggest that remnants of recent (0-8 Gyr ago) accretion events, which correspond to the last few tens of percent of...
Fig. 1.6 Bottom row: externally-viewed snapshots showing the surface brightness of individual accretion relics in models of Milky Way-like stellar halos by Johnston et al. (2008). The three main morphological types identified in this study are illustrated: “great circle” streams (or “arcs”; left panel) arise from satellites accreted ∼6-10 Gyr ago on nearly circular orbits; “cloudy” morphologies (also dubbed “shells” or “plumes”; middle panel) arise from accretion events within the past ∼8 Gyr that fell in on eccentric orbits; and “mixed”-type tidal remnants (right) arise from ancient (more than 10 Gyr ago) accretion events that have had ample time to fully mix along their orbits. Top row: observational archetypes of each type of tidal debris from the survey by Martínez-Delgado et al. (2010): great circle stream in NGC 5907 (left), shell-like features around NGC 4651 (middle); and “mixed” debris near NGC 5866 (right panel).

mass accretion for a Milky Way-like spiral, should remain visible as substructures in presently observable stellar halos. These models also make predictions about what can be physically inferred from an external, “global” view of stellar halos. For example, from the shapes of debris remnants, we can infer the basic dynamical properties of the progenitor — Johnston et al. (2008) demonstrates that tidal debris of different morphologies each occupy different regions in the time of accretion vs. orbital eccentricity/energy plane (see their Fig. 3), and that surface brightness also gives evidence of both the time of accretion and the luminosity of a remnant’s progenitor (see Fig. 4 of Johnston et al.). While this gives some general insight into properties of the accretion events, there is considerable degeneracy in the inference of such properties, which may best be thought of as providing reasonable estimates upon which to base specific modeling of the accretion events.
Figure 1.6 compares the predicted morphologies of model debris structures from Johnston et al. (2008) to observed structures in external galaxies, demonstrating that we see examples of the remnants predicted by the models in the local Universe. The classifications of debris structures suggested by Johnston et al. include: “great circles” – streams that arise from satellites on nearly circular orbits that were accreted $\sim 6 - 10$ Gyr ago; “cloudy” morphologies (also known as “shells” or “plumes”) resulting from recently-accreted (less than $\sim 8$ Gyr ago) satellites that were on rather destructive, radial orbits; and “mixed”-type tidal remnants from ancient accretion events (more than $\sim 10$ Gyr ago) that have had time to phase mix and become non-descript. While these simulations make detailed predictions about the total number, frequencies, and specific properties of halo substructures, there is no analogous observational data set to which these simulations can be compared en masse. As demonstrated in Figure 1.6, some observational examples of different stream morphologies have been identified in the local Universe, including “great circles” in NGC 5907 (Shang et al., 1998; Martínez-Delgado et al., 2008) and M 63 (Chonis et al., 2011; see also Figure 1.1), the “plume”-like feature (or “umbrella”) in NGC 4651 (Martínez-Delgado et al., 2010), and a feature of “mixed” morphology around NGC 1055 (Martínez-Delgado et al., 2010).

Generally, it is easiest to infer the physical properties of great circle streams, as the great circle is a reasonable tracer of the progenitor’s orbit. Analytical relationships derived by Johnston et al. (2001) may be used to estimate the accretion time and total (dark matter+stellar+gas) initial mass of the progenitor of a stream on a great circle. Surface photometry across streams in multiple filters can be used to infer the stellar populations and total stellar mass for the stream (similarly to integrated light mapping of stellar mass surface density in external galaxies; e.g., Zibetti et al. 2009). Variations in the optical colors along the stream can be used to infer changes in the mean properties of the stellar populations, but are on the whole less diagnostic than similar studies using resolved stars in the Local Group. However, extraction of meaningful properties from the integrated light of streams requires S/N $>5$-10 above the local background fluctuations over a sufficiently wide area to cover the full stream. Thus, not only must the image be deep, but the backgrounds need to be well characterized. This can be seen in Figure 1.1, which shows that while hints of debris may be identifiable in SDSS imaging (e.g., Beaton et al. 2014), extraction of physical properties requires deep, well-characterized imaging.

Cooper et al. (2010) coupled the Aquarius simulations to a state-of-the-art semi-analytic model known as GALFORM, which computes the properties (mass, size, star formation history and chemical abundance) of the galaxy forming in each dark matter halo. The GALFORM model is constrained through statistical comparisons to collective properties of the cosmological galaxy population (for example, optical and infrared luminosity functions), and by requiring that the surviving counterparts reproduce the observed size-luminosity relationship for Milky Way dwarfs. To meet these constraints, this technique demands fine-grained simulations such as Aquarius in order to adequately resolve the star-forming cores of satellite halos. This approach results in a set of dynamically self-consistent $N$-body realizations of stellar halos and their associated tidal streams at a resolution beyond the reach of current hydro-
Fig. 1.7 Expected halo streams around a Milky Way-like galaxy from a simulation (Bullock & Johnston, 2005). The figure shows an external perspective of one realization of a simulation within the hierarchical framework, with streams resulting from tidally disrupted satellites. The snapshot on the left is 300 kpc on a side (the virial radius for a Milky Way sized galaxy), and illustrates the result of a typical accretion history for a Milky Way-like galaxy. Right panels: theoretical predictions for the detectable tidal features in the same halo as the left panel, but assuming three different surface brightness (SB) detection limits: $A$: $\mu_{\text{lim}} = 28$, $B$: $\mu_{\text{lim}} = 29$ and $C$: $\mu_{\text{lim}} = 30$ mag arcsec$^{-2}$. Each snapshot is 100 kpc on a side. No discernible substructure is predicted for surveys with SB limits brighter than $\sim 27$–28 mag arcsec$^{-2}$ (e.g., POSS-II and SDSS). This result also shows as the number of tidal features visible on the outskirts of spirals depends dramatically on the SB limit of the observations. Moreover, the brightest substructures tend to be from the most massive satellites, which sample relatively rare accretion events (Johnston et al., 2008; Gilbert et al., 2009).

dynamical simulations (e.g., Abadi et al., 2006), and without the need to invoke many of the approximations required by previous models (e.g., Bullock & Johnston, 2005). The individual star formation history of each satellite (and hence properties such as stellar mass, luminosity and net metallicity) can be studied alongside the full phase-space evolution of its stars.

Current models have sufficient numbers of particles to resolve the main contributors of bright, coherent substructures that are similar to tidal features detected in the current imaging surveys (e.g., Martinez-Delgado et al., 2010). Thus it is possible to make sky-projected snapshots of these stellar halos from different viewing angles and a selected photometric band. Each model halo has experienced a unique
merging history and provides predicted surface brightness, morphologies and overall distribution of the observable streams, survival of the progenitors and stellar populations (or mean colors), that can be compared with observational data. These snapshots can be used as the input source for creating a mock catalogue of synthetic images, which can be generated by adding simulated streams to real images including all the observational effects of the telescopes (e.g., typical sky noise, flat-field corrections, surface brightness limits, etc.) and contamination from other galactic substructures (e.g., the stellar disk that is not directly simulated by models of this type). An example of this technique using the Bullock & Johnston (2005) models as input is shown in Figure 1.7. These mock observations give preliminary predictions for the level of substructure detectable in the stellar halo of a nearby spiral for the typical surface brightness limits of current imaging surveys. Moreover, additional observational properties, like chemical compositions (both [Fe/H], [$\alpha$/Fe]), can be explored as they relate to the other properties of substructure, the most significant being the time since accretion and luminosity (or stellar mass), as was done by, e.g., Font et al. (2006).

The Bullock & Johnston (2005) halos all have some structure visible at surface brightnesses of $\sim$27-28 mag arcsec$^{-2}$. To surface brightnesses of $\sim$29 mag arcsec$^{-2}$ there is $\sim$1 visible stream in each simulated halo, and typically about 2 visible streams above $\sim$30 mag arcsec$^{-2}$. The majority of the substructure, and thus the majority of the accretion history, is at surface brightnesses fainter than $\sim$30 mag arcsec$^{-2}$. The degeneracy between the luminosity of the satellite, its accretion time, and its surface brightness is studied in depth by Johnston et al. (2008). Our inability to see the fainter streams, which were either accreted earlier or come from lower luminosity progenitors, implies that our view of halo substructure beyond the Local Group will be dominated by the most recent and/or most massive accretion event, and, in either case, the most metal rich populations (Johnston et al. 2008; Gilbert et al., 2009). Moreover, more massive accretion events tend to preferentially populate the innermost regions of the halo ($R_{\text{proj}} < 30$ kpc), as dynamical friction, which is more effective for more massive satellites, will cause the orbit of the progenitor to degrade (Johnston et al., 2008). Thus, our view of extragalactic tidal streams at relatively shallow surface brightness limits (i.e., those of POSS and SDSS) is highly biased to a specific subset of accretion events that are relatively rare for Milky Way sized galaxies.

1.5 The role of interactions within dwarf galaxy halos

Hierarchical formation models predict substructure should exist on all scales, not just around relatively massive galaxies like the Milky Way. Thus, exploration of the extended stellar structures of dwarf galaxies should reveal similar tidal features to those previously discussed. We first discuss the observational evidence for halos around dwarf galaxies and, in particular, for substructure in dwarf galaxy halos. Second, we discuss the impact that the creation of such substructures would
have on dwarf galaxies. Understanding the formation and evolution of dwarf galaxies is particularly vital to form realistic “initial conditions” for simulations and to make highly detailed predictions of substructure properties. For many reasons, extra-galactic systems are best suited for these explorations.

1.5.1 Observational evidence for substructure at dwarf galaxy scales

In the process of hierarchical structure formation, it is likely that some of the most massive satellite dwarf galaxies themselves host their own, even smaller satellites (dwarf spheroidals – “dSphs” – or globular clusters). In the Milky Way, we know that the most massive classical dwarf galaxies have globular clusters associated with them – specifically the Large Magellanic Cloud, the Small Magellanic Cloud, and the Fornax dSph (e.g., Forbes et al., 2000), as well as the Sagittarius tidal stream (e.g., Law & Majewski, 2010b). The most massive Milky Way satellite, the Large Magellanic Cloud (LMC), is itself part of a bound pair of dwarf irregular galaxies (with the Small Magellanic Cloud, or SMC). Thus, we would expect to find evidence of tidal interaction around dwarf galaxies, analogous to the features we see in halos of more massive galaxies. The majority of the dwarf galaxies in the Local Group are satellites, which have experienced interactions with their more massive host. Thus, it can be difficult to disentangle effects on the dwarf created during the accretion by its parent from those it experienced before falling in. Studying external, isolated dwarf galaxies may prove a more effective means of understanding the role of hierarchical formation, including the role interactions may have in forming the Hubble sequence at low masses.

In fact, many of the unique features of the LMC-SMC pair can be explained by their binary interaction (e.g., Besla et al., 2012), including the spectacular 200° Magellanic Stream in HI (Nidever et al., 2010). Binary pairs are somewhat rare, as Robotham et al. (2012) find only two MW+LMC+SMC analog systems among the Galaxy Mass Assembly (GAMA) galaxies. While only 3.4% percent of GAMA galaxies are MW+LMC+SMC analogs, 12% of SDSS galaxies have LMC-like companions (i.e., luminous satellite within 75 kpc; Tollerud et al., 2011), which suggests that about one in four LMC-like satellites have a smaller SMC-like companion. The relatively low fraction of LMC-SMC binary satellite systems supports a “transient” nature, as detailed numerical simulations of the LMC-SMC suggest they may not remain a bound pair for long (Besla et al., 2012). In fact, it has been suggested (e.g., D’Onghia & Lake, 2008) that satellites should often fall in as pairs or in groups, rather than individually, and the dwarf galaxies found at the edge of the Local Group (representing future accretions) are grouped (e.g., Mateo, 1998; McConnachie, 2012). Thus, we would expect to find evidence of tidal interaction around dwarf galaxies, analogous to the features we see in halos of more massive galaxies.
Wide-field optical and near-infrared imaging has revealed stellar halos around many star-forming dwarf galaxies in and beyond the Local Group (see Stinson et al. [2009] for an extensive listing of many of these). While Stinson et al. determined that these extended stellar envelopes are not likely to arise due to tidal interactions with the (larger) host galaxies, it has not been determined whether they are the result of interactions with smaller satellites. Large area surveys of the most massive dwarf galaxies in the Local Group also indicate the presence of extended, “halo-like” stellar populations at large effective radii, including M 33 (McConnachie et al. 2009), the LMC (Nidever et al. 2007), and the SMC (Nidever et al. 2011). Further characterization, including full kinematic profiles, is necessary to determine if these extended structures are lower mass versions of the halos found around Milky Way sized galaxies.

One of the many probable dwarf galaxies discovered by Karachentsev et al. (2007) was an elongated feature near the dwarf irregular galaxy NGC 4449 in Digitized Sky Survey (POSS-II) plates (denoted as object “d1228+4358” in their catalog). NGC 4449 is a dwarf starburst galaxy with an irregular morphology, with luminosity ($M_V = 18.6$) similar to that of the LMC, but with much stronger and more widespread ongoing star-formation activity. Its cold gas and HII regions exhibit peculiar kinematics (Hartmann et al. 1986; Hunter et al. 1998), suggesting that it may have recently interacted with another galaxy. Using deep, wide-field imaging around NGC 4449, Martínez-Delgado et al. (2012) definitively identified the Karachentsev et al. feature as a dwarf galaxy undergoing accretion by NGC 4449 (see Figure 1.8). This new dwarf galaxy was also seen by Rich et al. (2012) in a similar deep-imaging survey, which revealed the dwarf (dubbed NGC 4449B) and its S-shaped morphology that is characteristic of disrupting satellites. After fitting and subtracting a halo model, Rich et al. showed additional arcs and possible disk ripple features in the residual stellar surface brightness maps, along with evidence for a break in the surface brightness profile of the NGC 4449 stellar halo. The morphology, size, luminosity, and surface brightness profile of the newly discovered stream/dwarf, along with evidence of tidal features in the NGC 4449 halo and outer disk, was suggested by Rich et al. (2012) to result from a dwarf (NGC 4449B) that is on its first passage, and passed near the center of its host $\sim 10^8$ yr ago. Thus, NGC 4449 is the first direct evidence of hierarchical structure formation similar to that seen in Milky Way-type galaxies, but on the mass scale of dwarf galaxies.

1.5.2 Implications of dwarf-dwarf interactions

It is worth noting that the first stream from a dwarf-galaxy accretion event was found around one of the most intensely star-forming nearby galaxies. This leads one to wonder whether such accretion events are common among dwarf galaxies in recent epochs. It is possible that exact analogs to this stream have not been noticed in POSS or SDSS images because they are uncommon. However, another explanation is that the majority of such structures are fainter, more diffuse, or at a larger radius than
Fig. 1.8 The stellar stream around the dwarf galaxy NGC 4449. Left: greyscale image from Martinez-Delgado et al. (2012) with a color inset for the galaxy, which clearly indicates the presence of an S-shaped tidal stream approximately 7 kpc in length. There is no clear association with any of the existing HI gas features (Hunter et al., 1998). Right: Subaru telescope sub-arcsec resolution image of the stellar stream (Martinez-Delgado et al., 2012). This is one of the few extragalactic stellar streams that has been resolved into individual stars, which provides direct probes of its stellar populations.

The NGC 4449 stream, and thus await future detection. If streams as in NGC 4449 are common around dwarfs, they re-ignite classic ideas about galaxy interactions triggering starbursts. Given the high rates of star formation in dwarf galaxies, it is natural to ask if satellites are responsible. Surveys along these lines have produced mixed results (Noeske et al., 2001; Brosch et al., 2004; Li et al., 2008), but these studies were not looking for objects like the detected dwarf satellite of NGC 4449 – a gas poor, low-surface brightness analog to the Local Group dSphs – and did not probe appropriate depths to find these objects. Regardless of the implications for starbursts, evidence from NGC 4449 and the Fornax dSph, which shows traces of having swallowed a smaller dSph (Coleman et al., 2005), suggests that accretion of even smaller building blocks is a viable avenue for direct assembly of dwarf galaxy stellar halos.

It has been proposed that dSphs orbiting massive galaxies such as the Milky Way may be the result of “pre-processing” which is a term for the effects of interactions within groups of dwarf galaxies (e.g., D’Onghia et al., 2009). More specifically, it has been suggested that the dSphs were once gas-rich, rotationally supported objects like the field galaxies (i.e., similar to NGC 4449) whose properties were modified
into the gas-free, dispersion supported dSphs via interactions with companions. This is a compelling scenario for the class of dwarf galaxies in the Local Group known as “dwarf Transition” objects (see [Mateo 1998; Grebel 1999 among others]), whose properties are intermediate between those of dIrrs and dSphs. Evidence of a dwarf-dwarf interaction in NGC 4449, in conjunction with the known HI streams around this dwarf galaxy, may thus demonstrate such a process in action. Moreover, [Nidever et al. 2013] identified an HI filament associated with the M 31 dwarf satellite IC 10. The dynamics and orientation of the stream are inconsistent with the orbital parameters of IC 10, and [Nidever et al. 2013] suggest that the stream and other atypical HI features in the IC 10 disk could be explained via interaction with a “stealth” companion.

[Wetzel et al. 2015] used the ELVIS simulations to explore the frequency of “pre-processing” for satellites within a simulated Milky Way host and found that nearly half of all satellites with stellar masses less than 10^6 solar masses were pre-processed in a more massive satellite halo. More generally, satellites with lower stellar masses or those closer to their host are more likely to have undergone pre-processing. Recent observational work for the Milky Way and M 31 also provides hints of associated satellites or debris, including potential satellites with similar line-of-sight velocities (e.g., Chapman et al. 2007; Martin et al. 2009; Tollerud et al. 2012) and potential kinematic associations between substructures (e.g., Deason et al. 2014). While these initial probes are tantalizing, full phase space realizations of these objects that are only permitted via precision distances and proper motions are required to fully explore these associations locally. Moreover, though it is tempting to explain morphological transitions with dwarf-dwarf interactions, there is significant degeneracy with other physical processes that can alter HI morphologies even at large radius in a group environment, for instance the effects of ram pressure from the hot gaseous halo can be quite dramatic (see case studies in McConnachie et al. 2007; Kenney et al. 2014) and many isolated gas-poor dwarfs could be the result of “fly-by” interactions with their host (see Teyssier et al. 2012). However, the HI debris created by dwarf-dwarf interactions and ram pressure are different, and finding more dwarf galaxies in “distress” will reveal the relative importance of these processes, which also have implications for their halo substructures.

A dramatic example of an ongoing dwarf-dwarf interaction was seen by [Paudel et al. 2015], who found a pair of dwarf galaxies connected by a 15 kpc stellar bridge. The HI disk for one of the galaxies is “completely destroyed” and there are several knots of star formation that have global properties similar to either young globular clusters or ultra-compact dwarf galaxies. The Paudel et al. (2015) dwarf-dwarf merger bears a striking resemblance to a scaled down version of equal mass mergers at larger total masses. The importance of dwarf interactions in shaping stellar populations of low-mass galaxies is highlighted in a recent systematic, multi-wavelength study of the relative star formation rates in interacting pairs of dwarf galaxies (TiNy Titans, or TNTs) by [Stierwalt et al. 2014]. This work found clear evidence of star formation enhancement (by a factor of \( \sim 2.3 \pm 0.7 \)) among paired dwarfs relative to their unpaired counterparts. This enhancement occurs even in interacting pairs that are isolated by \( D > 1.5 \) Mpc from their nearest massive neighbor, showing that
galaxy interactions are a frequent driver of enhanced star formation even outside
the influence of larger galaxies. The Stierwalt et al. 2014 study also finds a factor
of $\sim 3$ increase in the fraction of paired dwarfs that are starbursting relative to sin-
gle dwarfs, further highlighting the role of interactions in triggering star forming
episodes. Thus far, though, stellar tidal debris signatures of these dwarf-dwarf inter-
actions have not been identified. [Note that this study is limited to pairs of mass ratio
$(M_1/M_2) < 10$, while the disrupting companion to NGC 4449 has about 1/50th its
stellar mass (Martínez-Delgado et al. 2012).]

1.6 Induced star formation, disk structure, and tidal streams

Simulations of structure formation on galactic scales in the prevailing $\Lambda$CDM
paradigm predict that Milky Way-sized host galaxies should accrete several mas-
seve satellites from $z \simeq 1$ to the present. We now consider the effects of these inter-
actions on the disk of the parent galaxy. Given the significantly shorter dynamical
timescales in the disk, the potential effects of a even a minor accretion event could
be profound. In particular, such events could incite abnormal structures in dissipa-
tional HI disks, either creating features after a pass through or creating large scale,
global distortions in the HI structure. In the stellar component of the disk, the effects
could be both more subtle and more long lived.

One example of a burst of star formation in a Milky Way-like galaxy with an
associated recent accretion event is seen in NGC 5387 (Beaton et al., 2014, note
that NGC 5387 can be considered a Milky Way analog based on its properties, but
contains about an order of magnitude less mass than the MW). This system shows
a low surface-brightness feature in SDSS imaging, that was explored with deeper
imaging by Beaton et al., who found a stellar stream extending over at least an en-
tire orbital wrap, with median surface brightness of $\sim 24.5$ mag arcsec$^{-2}$ in $R$-band
(see Figure 1.9). This stream has a redder color than the typical stellar populations
of NGC 5387, and contains a total stellar mass of $\sim 6 \times 10^8 M_\odot$. Coincident with
the position of the stream’s crossing of the NGC 5387 disk is a “blue overdensity”
that is not only blue in optical colors, but is producing a large FUV flux as well.
Evidence from the FUV flux as well as follow-up spectra obtained by Beaton et
al. (2014) suggests a very recent ($\sim 8$ Myr ago) star formation event of total stel-
lar mass $2.5 \pm 1.3 \times 10^7 M_\odot$. Beaton et al. conclude that this blue overdensity is a
complex of multiple HII regions produced by star formation either induced in the
disk by the minor merger event, or in the dwarf galaxy progenitor of the stream
itself. Whichever scenario is shown to be true, it is clear that the blue overdensity
and its associated tidal stream represent star formation induced by the accretion
of a satellite about 1/50th the mass of its host.

The presence of tidal streams encircling galaxies with warped disks (see, e.g.,
Martínez-Delgado et al. 2008) may suggest satellite galaxy perturbations as the or-
igin of those disk features (e.g., Velazquez & White 1999, Weinberg & Blitz 2006).
This suggests that promising galaxies to search for extragalactic tidal streams are
Fig. 1.9 Images of the stream and associated blue overdensity in NGC 5387. The left panel is the $R$-band image from the VATT, with the SDSS color image inlaid in the central regions, and clearly shows a full wrap of tidal debris about the disk of NGC 5387. The right panel shows a merged image composed of the SDSS, VATT, and GALEX FUV images, which more clearly highlights the blue overdensity near the northernmost edge of the disk of NGC 5387. The inset in the right panel is a schematic highlighting the disk in dark gray, the stream as a lighter gray loop, the blue overdensity as a blue circle, and two foreground stars. [Reproduced from Beaton et al. (2014).]

those that display disk asymmetries in optical or HI images that may result from gravitational interaction with the tidally disrupting companions. One striking case
of such a system is NGC 4013, an isolated spiral galaxy with a prominent HI warp (Bottema et al., 1987) that has been revealed by deep imaging (Martínez-Delgado et al., 2009) to contain a faint loop-like stellar tidal stream at fairly low inclination to the disk (see the upper panels of Figure 1.1). The sky-projected morphology of this structure displays a remarkable resemblance to an edge-on view of models of the Monoceros Ring feature (see Chapter 3) in the Milky Way as a tidal debris structure (Peñarrubia et al., 2005). This suggests that the progenitor system of the NGC 4013 stream may have been a low-mass satellite on a low-inclination, nearly-circular orbit that was accreted approximately \( \sim 2.8 \) Gyr ago. Stellar streams have also been discovered in the warped spiral galaxies NGC 5907 (Martínez-Delgado et al., 2008, see also Figure 1.3) and M 63 (Chonis et al., 2011, see also Figure 1.1), showing that disks that are apparently undisturbed as seen in the optical, but warped in HI maps, may reveal signatures of recent accretion events in deep imaging surveys.

It has been shown that such accretion events should lead to strong warping, flaring, and thickening of an initially cold stellar disk (Kazantzidis et al., 2008), and to the generation of bars and spiral structure (e.g., Toomre & Toomre, 1972; Gauthier et al., 2006; Dubinski & Chakrabarty, 2009; Purcell et al., 2011). Such perturbations may also lead to the formation of long-lived, ring like stellar features in the outer reaches of the disk that may extend several kiloparsecs from the disk plane, and have surface brightnesses in the range of 25-30 mag arcsec\(^{-2}\) (see Fig. 6 of Kazantzidis et al., 2008). Indeed, observations in the Milky Way are uncovering wave like perturbations in the disk in stellar densities (Widrow et al., 2012; Yanny & Gardner, 2013; Xu et al., 2015) and velocities (Gómez et al., 2012a, b; Carlin et al., 2013; Williams et al., 2013), with an accompanying array of simulations predicting the formation of such features (e.g., Chakrabarti & Blitz, 2009; Michel-Dansac et al., 2011; Purcell et al., 2011; Gómez et al., 2013; Faure et al., 2014; Widrow et al., 2014). Evidence for dynamically heated populations is not unique to the Milky Way – Dorman et al. (2013) have identified a kinematically cold population in the halo of M31.

### 1.7 Future prospects

While the study of tidal streams from major mergers/encounters (1:3 mass ratio) or even minor encounters (1:3 to 1:10 mass ratio) is an old field, the extension of these studies to those streams formed by satellite galaxies, a.k.a., micro-mergers (mass ratio < 1:10), is a relatively new area of exploration. Study of mergers on this mass scale provide a direct way of addressing some open questions on galactic formation and evolution. In the last decade, the observational effort has yielded an unprecedented sample of bright stellar streams in nearby spiral galaxies, including the discovery of observational analogs to the canonical morphologies found in \( N \)-body models of stellar halos (Johnston et al., 2008, see chapter 6). This offers a unique opportunity to study in detail the apparently still dramatic last stages of galaxy assembly in the local universe and to probe the anticipated estimates of frequency of tidal stellar features from the \( \Lambda \)-CDM paradigm for MW-sized galaxies.
Moreover, these discoveries demonstrate the need for deep, wide-field imaging that pushes fainter than current surveys in order to visualize external galaxy halos on par with the highly substructured portrait of our own Milky Way and M 31. Such studies will address the following key questions (among others) on several aspects of hierarchical galaxy formation:

- How many tidal debris features still exist as recognizable substructures in nearby spiral galaxies?
- Is the abundant number of stellar streams exceptional in the Local Group spirals, and are tidal streams as common as predicted by cosmological models?
- At what rate are stellar streams still forming in the local Universe?
- Are the tidal stream properties (e.g., mean surface brightness) observed in the local Universe consistent with predictions from Λ-CDM simulations?
- What can we learn about baryonic processes within dark matter halos from observations of these stellar halo substructures?
- What is the (stellar) mass spectrum of the streams, and hence the mass spectrum of the progenitor satellites?
- What is the fraction of halo stars attributable (within data limitations) to distinct structures?
- Do all dwarf galaxies contain evidence of hierarchical accretion, and what is the role of such interactions in forming the progenitors of streams in larger galaxies?
- Do streams (or their progenitor satellites) contribute to disk heating and the formation of morphological perturbations observed in nearby galaxies?
- What is the incidence of low-inclination streams and what is their role in reshaping the outer disks of nearby spiral galaxies?

The study of external tidal streams also has the potential to tackle a significant number of other topics that are the focus of current astrophysical research (e.g., stellar populations of halos, the resilience of the disks involved with minor mergers, accretion of globular clusters, induced star formation in streams, near-field cosmology, satellite dynamics, dark matter halo shapes, etc.). In particular, the interpretation of global properties of galaxy halos and outer disks from resolved stellar populations (from, e.g., the Hubble Space Telescope survey GHOSTS; Radburn-Smith et al. [2011] or the CALIFA high-resolution spectroscopy survey of nearby stellar systems; Sánchez et al. [2013]) requires understanding the role and prevalence of tidal debris in galaxy halos. In addition, studying stellar population gradients along tidal streams via deep HST photometric data (see, e.g., Aloisi et al. [2005]) will render important constraints on the effect of tides on the stellar formation history of dwarf galaxies. The panoramic view of tidal streams in external galaxies also offers an excellent opportunity to demonstrate tidal stripping of globular clusters formed in satellite galaxies, which may correspond to an important fraction of the globular cluster population of the host, as earlier proposed by Searle & Zinn [1978]. Ultimately, the ideal scenario would require resolving stellar populations in large numbers of galaxies at distances of 10-20 Mpc, which will be feasible in the next one or two decades with thirty-meter class ground-based telescopes or the proposed suite of space-based instrumentation.
Finally, the future census of tidal streams and their properties will also provide an essential framework for exploring whether the Milky Way is a template for the archetypal spiral galaxy. The next generation of galactic surveys (LSST) and future astrometric space missions (Gaia) will dissect the structure and formation of the Milky Way with unprecedented detail, leading to a revolutionary improvement of our understanding of the Galaxy. In this regard, the study of these structures in external systems will be complementary in interpreting this local Galactic archaeological data in the context of galaxy formation and evolution, providing unique data in order to quantify how typical the Milky Way is with respect to other nearby galaxies of its type.

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