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LETTER TO THE EDITOR

Stellar Tidal Streams Around Milky Way Analogs in the Local Universe

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ABSTRACT

Context. The stellar tidal streams are the result of tidal interactions between a central galaxy and lower mass systems like satellite galaxies or globular clusters. For the Local Group, many diffuse substructures have been identified and their link to the galaxy evolution has been traced. However it cannot be assumed that the Milky Way or M31 are representative of their galaxy class, and a larger sample of analog galaxies beyond the Local Group is required to be able to generalise the underlying theory.
Aims. We want to characterise photometrically the stellar streams around Milky Way analogs in the local Universe with the goal to deepen our understanding of the interaction between host and satellite galaxies, and ultimately of the galaxy formation and evolution processes.
Methods. In the present work we identified and analysed stellar tidal streams around SAGA Milky Way analog galaxies, including the measurement of their surface brightness and colors using GNU Astronomy Utilities software.
Results. We obtained and analysed the frequency and photometric parameters for 28 Milky Way analog galaxies, including a comparison of the surface brightness and colors of the streams, their progenitors, and the dwarf satellite galaxies population around galaxies belonging to the same SAGA sample
Conclusions.

Key words. tidal streams – MW analogs – satellite galaxies –

1. Introduction

Over the last two decades, studies focused on the formation and evolution of our Galaxy have been significantly advanced by the first generation of wide-field, digital imaging surveys and the Gaia astrometric mission. The extensive photometric databases that resulted have provided, for the first time, spectacular panoramic views of the Milky Way tidal streams (Belokurov et al. 2006; Ibata et al. 2007; Ibata 2019; McConnachie et al. 2009; Shipp et al. 2018) and revealed the existence of large stellar sub-structures in the halo, which have been interpreted as observational evidence of our home Galaxy's hierarchical formation. Furthermore, the PAndAS Survey (McConnachie et al. 2009) has revealed a panoramic view of the Andromeda halo with a multitude of tidal streams, arcs, shells and other irregular structures that are possibly related to ancient merger events. These observations confirm the ΛCDM prediction that tidally disrupted dwarf galaxies are important contributors to the formation of Galactic stellar halos. The next generation of Galactic and extragalactic surveys (e.g. LSST) will dissect the stellar halo structure of these Local Group spirals with unprecedented detail, promising further improvements in our understanding of the early formation and merger history of the Milky Way.

While some of the known Milky Way and M31 stellar streams can be well characterized in a wide parameter space and also using observations of their individual stars, results for individual systems are not easy to compared to with numerical simulations due to the natural stochasticity of galaxy assembly histories in the ΛCDM model. Although statistical distributions, for example of halo assembly times or satellite luminosities, are well-defined for galaxies selected in a narrow range of stellar mass and/or halo mass, individual systems may show large deviations from the mean. To overcome this limitation, a search for streams and other merger debris in a larger sample of Milky Way-like galaxies is required. This is a daunting task. Because of their extremely faint surface brightness, the observed frequency of stellar streams is very low even in ultra-deep imaging surveys; see Hood et al. (2018) for a modern review.

Although tidal tails from major mergers (or even minor mergers with merger mass ratio < 1:10) have been extensively studied, there have been few attempts to survey higher mass ratio 'micro-merger' events (characteristic mass ratios of ∼ 1:50 - 1:100). In this paper, we will focus only on these events, which we call *stellar tidal streams*, arising from the tidal disruption of dwarf galaxies. We exploit the deep, wide-field imaging from the DESI Legacy Surveys **(DESI Collaboration et al. 2016a,b)** to systematically explore the frequency and photometric properties of streams in the stellar halos of more than 200 Milky Way analog targets previously selected for the *Satellites Around Galactic Analogs* (SAGA) survey (Geha et al. 2017; Mao et al. 2021). The goal of SAGA is to obtain highly complete samples of satellite galaxies around many Milky Way-like systems, in order to overcome system-to-system variations and carry out a robust statistical comparison of their properties to models. The SAGA host galaxies were selected to be an approximately stellar mass-limited sample based on their total K-band luminosity (used as a proxy for stellar mass) and isolation. SAGA provides a clearly defined sample of Milky Way-like analogues that we use as the basis for our parallel survey of stellar streams in the local Universe. SAGA will also provide a detailed characterization of the satellite population in the same sample, which will allow us to compare the surviving and disrupted satellite populations to one another, and to models, on a firm statistical footing.

2. Methodology

2.1. Image Sample

The second phase of the SAGA survey (Mao et al. 2021) defines a parent sample of Milky Way-like host galaxies with absolute K-band magnitude in the range $-23 < M_K < -24.6$ mag, approximately equivalent to the stellar mass range $10^{10} < M_\star < 10^{11}$ $M_\odot$. The sample excludes close pairs of hosts, defined by a host-satellite K-band magnitude difference of $\Delta K < 1.6$ mag. The SAGA survey only carried out spectroscopic follow-up for hosts in this parent sample with distances $25 < d < 40.75$ Mpc. Here we base our study on the full SAGA II parent sample, including galaxies within $d < 25$ Mpc, which therefore comprises 226 Milky Way analogs with distances $d < 40.75$ Mpc. Further details of the SAGA II parent sample can be found in Mao et al. (2021).

From a visual inspection of the images of the resulting sample, and using the Legacy Survey Sky Browser[1] we selected as targets for our photometric analysis those galaxies where a stellar tidal stream could be identified. From this visual inspection, a total of 28 galaxies with detected streams were selected, for which six galaxies are at a distance < 20 Mpc (identified in the Nearby SAGA subsample), while the rest of targets are at larger distances, up to 40 Mpc. Image cutouts of these selected targets were then computed from the raw data from the *DESI Legacy Imaging Surveys* (DESI Collaboration et al. 2016a,b, ; LS) using a modified version of the LS reduction pipeline *Legacypipe*. The modifications... (see Martinez-Delgado et al. 2021). The resulting wide-field images reach surface brightness limits as faint as 29 mag arcsec^{-2} in the r band (see Section 2.2), ensuring a sufficient image depth to be able to measure very faint tidal structures. The images analysed in this work are listed in Table 1 (While streams could be detected in NGC4013 (Martinez-Delgado 2010) and NGC5866, the corresponding images presented artifacts and over-subtraction and consequently, photometry measurements could not be performed reliably, and are not shown in this table) and a sample of them is shown in Figure 1.

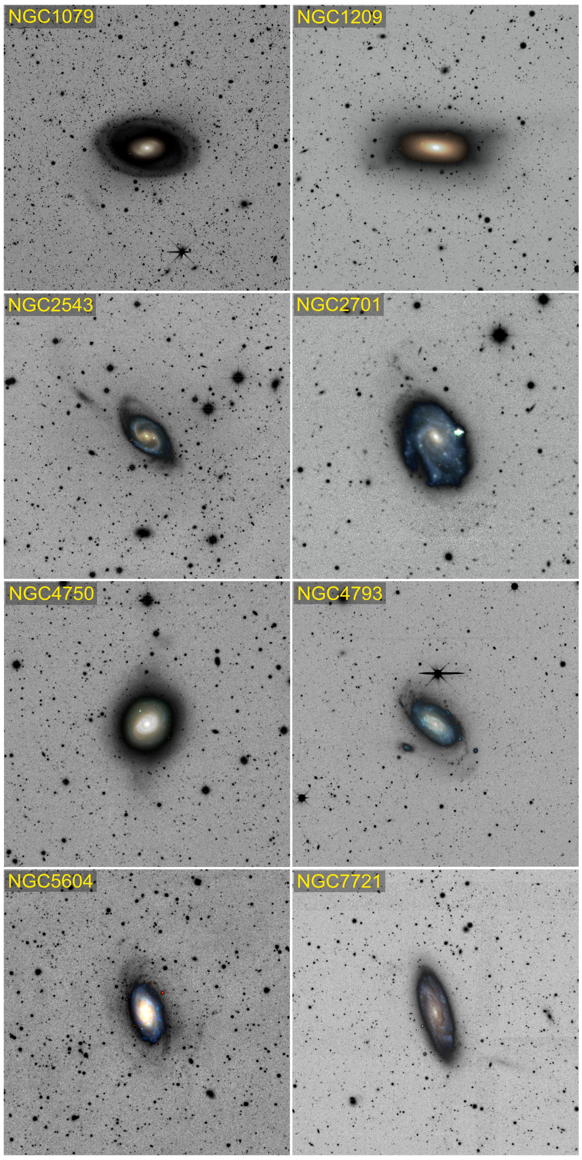

Fig. 1. Sample of images showing stellar streams around galaxies listed in Table 1. For illustrative purposes, shallower color images (also from the *DESI Legacy Imaging Surveys*) have been superimposed on saturated central region of each host galaxy.

2.2. Data Analysis

We carried out the photometric analysis with *GNU Astronomy Utilities* (Gnuastro)[2] a novel open source software package focused on the detection of low surface brightness sources. We made all the measurements by applying the Gnuastro's MakeCatalog subroutine on the sky-subtracted images generated by Gnuastro's NoiseChisel (Akhlaghi and Ichikawa 2015; Akhlaghi

[1] http://www.legacysurvey.org

[2] http://www.gnu.org/software/gnuastro

Table 1. Photometry of stellar streams around MW analog galaxies. Column 1 gives the name of the host galaxy; column 2 shows the surface brightness limit in the r band calculated in this work; columns 3 and 4 show the *Detection Index*, as defined in Martinez-Delgado et al. (2021). Columns 5 to 7 show the surface brightness in the g passband, in the r passband, and the $(g-r)$ color of the streams, averaged over all the apertures placed on the stream; column 8 indicates whether the stream has been reported for the first time in *this work*, indicated by (∗), or in one of the following previous works: (1) Martinez-Delgado (2010); (2) Martinez-Delgado et al. (2021); (3) Paudel & Ree (2014); (4) Morales et al. (2018); (5) de Blok et al. (2014).

Host	$\mu_{\rm r,limit}$	$\rm DI_{stream}$		$\langle\mu_g\rangle_{\rm stream}$	$\langle\mu_r\rangle_{\rm stream}$	$\langle g-r\rangle_{\rm stream}$	Discovered
		maximum	average				
	[mag arcsec^{-2}]	σ	σ	[mag arcsec^{-2}]	[mag arcsec^{-2}]	[mag]	
NGC0636	28.88	45.58	31.86	26.66 ± 0.03	25.86 ± 0.02	0.79 ± 0.04	(∗)
NGC1079	28.78	15.24	11.31	27.51 ± 0.05	27.00 ± 0.05	0.51 ± 0.07	(∗)
NGC1084	28.92	32.42	19.28	27.14 ± 0.03	26.61 ± 0.03	0.52 ± 0.04	(1)
NGC1097	28.86	unrel.	unrel.	27.07 ± 0.03	26.38 ± 0.03	0.70 ± 0.04	(∗)
NGC1209	28.91	unrel.	unrel.	28.71 ± 0.05	27.98 ± 0.03	0.73 ± 0.07	(∗)
NGC1309	28.76	24.42	23.02	25.66 ± 0.02	26.26 ± 0.02	0.61 ± 0.02	(∗)
NGC2460	28.81	10.39	8.06	27.50 ± 0.05	26.57 ± 0.04	0.93 ± 0.02	(∗)
NGC2543	28.55	10.18	9.00	26.66 ± 0.06	25.86 ± 0.06	0.80 ± 0.08	(∗)
NGC2648	28.19	22.70	16.62	26.49 ± 0.03	25.96 ± 0.04	0.53 ± 0.05	(∗)
NGC2701	28.58	6.63	5.55	26.85 ± 0.07	26.47 ± 0.08	0.40 ± 0.10	(∗)
NGC2782	28.51	28.69	20.55	26.14 ± 0.01	25.63 ± 0.02	0.51 ± 0.02	(∗)
NGC3614	28.57	9.79	6.64	27.78 ± 0.06	27.07 ± 0.05	0.70 ± 0.08	(∗)
NGC3689	28.00	10.75	6.45	27.55 ± 0.05	26.82 ± 0.05	0.74 ± 0.07	(2)
NGC4203	28.47	29.89	22.71	25.64 ± 0.02	25.13 ± 0.02	0.51 ± 0.02	(3), (4)
NGC4378	28.21	unrel.	unrel.	27.24 ± 0.03	26.53 ± 0.03	0.71 ± 0.04	(∗)
NGC4414	28.00	10.46	8.70	28.04 ± 0.15	26.75 ± 0.09	unreliable	(5)
NGC4750	28.57	54.58	35.07	26.81 ± 0.02	26.30 ± 0.03	0.51 ± 0.03	(∗)
NGC4793	28.11	20.02	18.04	26.16 ± 0.04	25.60 ± 0.06	0.57 ± 0.07	(∗)
NGC4799	27.93	8.49	6.98	26.65 ± 0.04	26.20 ± 0.07	0.45 ± 0.08	(∗)
NGC5297	28.55	28.00	18.58	26.35 ± 0.04	25.70 ± 0.04	0.65 ± 0.05	(∗)
NGC5493	28.30	32.96	28.06	26.38 ± 0.02	25.69 ± 0.02	0.68 ± 0.003	(∗)
NGC5604	28.18	12.29	9.93	26.35 ± 0.05	25.81 ± 0.05	0.54 ± 0.07	(∗)
NGC5631	28.54	12.88	10.01	27.60 ± 0.04	26.98 ± 0.04	0.62 ± 0.06	(∗)
NGC5750	28.23	29.41	27.37	27.38 ± 0.05	26.69 ± 0.04	0.69 ± 0.06	(4)
NGC5812	28.38	55.09	30.73	26.54 ± 0.04	25.67 ± 0.02	0.87 ± 0.04	(∗)
NGC7721	27.87	11.73	8.85	26.64 ± 0.05	26.30 ± 0.07	0.36 ± 0.07	(∗)

Table 2. Comparison between the average $g-r$ color of each streams and the corresponding color of its visually identified progenitor.

Host	$\langle g-r\rangle_{\rm stream}$ [mag]	$\langle g-r\rangle_{\rm progenitor}$ [mag]	Δ [mag]
NGC2543	0.80 ±0.08	0.59 ± 0.02	0.21 ± 0.08
NGC2648	0.53 ±0.05	0.60 ±0.003	-0.07 ± 0.05
NGC3614	0.70 ±0.08	0.67 ±0.08	0.03 ± 0.11
NGC3689	0.74 ±0.07	0.62 ±0.02	0.12 ± 0.07
NGC4793	0.57 ±0.07	0.41 ±0.01	0.16 ± 0.07
NGC5297	0.65 ±0.05	0.66 ±0.004	-0.01 ± 0.05
NGC5750	0.68 ±0.06	0.62 ±0.02	0.06 ± 0.06
NGC5812	0.87 ±0.04	0.73 ±0.005	0.14 ± 0.04
NGC7721	0.50 ±0.05	0.51 ±0.05	-0.01 ± 0.07

2019). The program also provides us with the errors in the photometry[3].

Our photometric analysis includes measurements of surface brightness in the LS r, g and z passbands for each galactic system and stream. Taking advantage of the depth and photometric quality of the LS survey images, we have also measured the $(g-r)$ colour of the streams. To our knowledge, beyond the Local Group, there are no comparable colour estimates in the literature for large samples of faint tidal streams. Our measurements add to those presented in our proof-of-concept study (Martinez-Delgado et al. 2021), which used the same method. We do not report $r-z$ colours here, because our initial analysis showed significantly greater uncertainty in the z-band photometry at low surface brightness (colour errors $\gtrsim$ 0.1 mag). We measure the surface brightness limit of the images for the g, r and z passbands following the approach of Román et al. (2020), i.e. we report the value corresponding to $+3\sigma$ of the sky background in an area of 100 arcsec^2. Table 1 reports the surface brightness limit for the r band, which is representative of the depth of the corresponding images in other bands.

We measured surface brightness and colors using circular apertures, placed manually following closely the detection map of the stream generated by NoiseChisel, once all foreground and background sources were masked. Circular apertures were used for simplicity and flexibility to adapt to the stream contour, though in few cases where the stream shape so allowed, larger elliptical or polygonal apertures were used to reduce the measurement error. Regions where the stream surface brightness was judged to be significantly blended with light from the host galaxy were avoided. As an illustration of the method, Figure 2 shows an example of a stream on which apertures have been placed manually in order to perform the measurement. We obtain a representative surface brightness and color for each stream by taking the mean of the corresponding individual aperture measurements.

Table 1 shows the measured ranges of stream surface brightness to be $25.64 < \mu_g < 28.71$ and $25.13 < \mu_r < 27.98$ mag arcsec^{-2}, for the g and r bands respectively. This table also includes the so called *Detection Index* (DI), as defined in Martinez-Delgado et al. (2021), which is calculated by compar-

[3] https://www.gnu.org/software/gnuastro/manual/html_node/Magnitude-measurement-error-of-each-detection.html

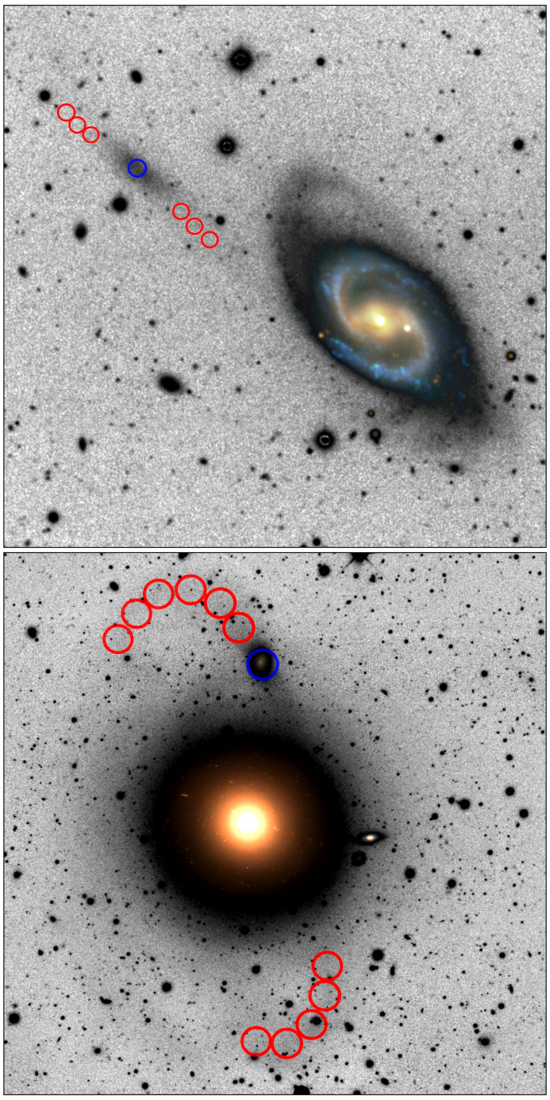

Fig. 2. Examples of our photometry measurement method, showing the apertures placed on the stellar streams around NGC5812 and NGC2543 along with the suspected progenitors, in order to measure their surface brightness and colors.

ing the measurements for a given aperture with the median and standard deviation of N random measurements in pixels with no source detection [4]. Measurements of surface brightness with error greater than 0.2 [mag arcsec^{-2}] or color with error greater than 0.1 [mag] are indicated as *unreliable* in Table 1 and discarded in the following analysis. For each stream, Table 1 also includes whether it has been discovered in this work or as part of previous efforts, giving the corresponding reference.

3. Results

We identified stellar tidal streams around 28 host galaxies from the parent sample of 226 MW analogs. This suggests that 12.4% $\pm$ 2.2% of the SAGA II galaxies have a stellar stream in the halo, for a r-band surface brightness limit range for our images between 27.8 and 29 mag arcsec^{-2} (see Table 1). This implies that, with 95% confidence, the percentage of typical SAGA sample halos that have an observable stellar streams is between 8.1% and 16.7%. This result is similar to that reported by Morales et al. (2018) for their systematic assessment of the frequency of tidal streams around a different sample of Milky Way-like galaxies in the local Universe. Morales et al. used co-added SDSS DR9 g, r and i band images processed using an image-enhancing technique similar to that of Miskolczi et al. (2011), with a typical surface brightness limited of 28.1 $\pm$ 0.3 mag arcsec^{-2}. They reported a total of 28 tidal streams from a sample of 297 galaxies, providing a conservative estimate that only $\sim$ 10% of galaxies show evidence of diffuse features that may be linked to satellite accretion events.

[4] https://www.gnu.org/software/gnuastro/manual/html_node/Upper-limit-magnitude-of-each-detection.html

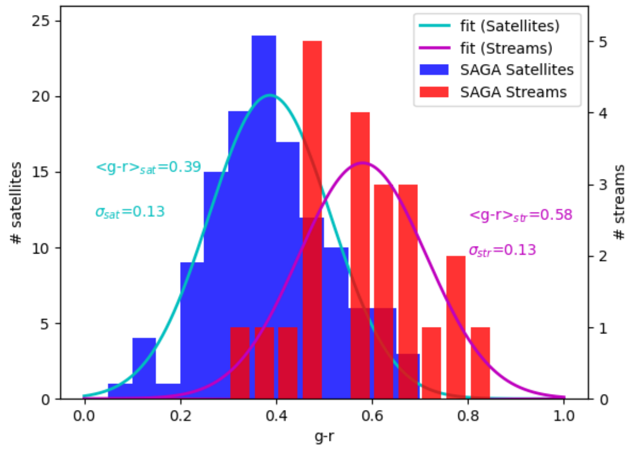

Fig. 3. Histogram showing the distribution of the average $g-r$ color of stellar streams around 22 galaxies from our sample, (those listed in Table 1 but without the nearby galaxies) together with the same color of the 127 satellite galaxies from the 36 SAGA systems sample.

Figure 3 compares the $g-r$ color distribution of the stellar streams identified in Table 1, shown in red, to that of the 127 spectroscopically confirmed satellite galaxies from the 36 SAGA systems presented in Mao et al. (2021), shown in blue. Streams around nearby galaxies (D < 20 Mpc) have been removed from our sample for the comparison, as these galaxies are not included in the SAGA sample. Normality analyses using hypothesis tests prove that these color distributions can be fitted by Gaussian distributions. The means and standard deviations are 0.58 $\pm$ 0.13 mag for the streams and 0.39 $\pm$ 0.13 mag for the SAGA satellites. The mean color of the streams is therefore 0.19 mag redder than that of the SAGA satellites, with a statistical confidence level larger than 99.999% (the p-value for rejecting the null hypothesis of equal colors is $< 10^{-9}$). The $g-r$ colors we find are similar to those obtained for the streams described in the proof-of-concept study of Martinez-Delgado et al. (2021), who reported a mean and standard deviation of 0.66 $\pm$ 0.12 mag. For comparison, have computed an average $g-r$ color of 0.51 $\pm$ 0.12 mag for dwarf galaxies in the Virgo cluster, from a gaussian fit to the data of Ferrarese et al. (2020). The Virgo dwarf satellites are redder than the SAGA satellites, as expected, since the Virgo dwarf galaxy population is mainly composed by very faint dwarf spheroidal galaxies that have been stripped of their gas due to environmental effects.

In approximately 35% of the streams in our sample, a highly likely progenitor can be identified by eye. This allows us to explore similarities and differences in the stellar populations of satellites and their streams, including the presence of population gradients along the streams As shown in Fig. 2 for the cases of NGC 2543 and NGC 5812, we placed apertures on the the likely progenitors as well as along the tidal features. Table 2 compares the $g-r$ color of the stream (averaged over the apertures as described in Section 2.2) with that measured in aperture on the suspected progenitor. We see a significant difference in color for the streams around NGC2543, NGC3689, NGC4793 and NGC5812, with the stream redder than its likely progenitor by 0.21, 0.12, 0.16 and 0.14 mag, respectively. For the rest of streams where a progenitor is suspected, the color difference is within the uncertainties of our color measurement, and therefore could be not conclusive. To test whether the differences observed in our sample are statistically significant or not, we have performed a hypothesis test of the difference between the stream and the progenitor colors, and we have obtained that streams are, in average, 0.05 ± 0.02 mag redder that their progenitor, with a confidence level > 99.99%.

4. Conclusions

The main conclusions of this letter are as follows:

- We have developed a new methodology, based on Gnuastro, for measuring the surface brightness and colours of streams.
- We have applied this methodology to enhanced DESI Legacy Imaging Survey *grz* data for a subset of the SAGA sample (a stellar mass-selected sample of Milky Way analogues at distances up to 40 Mpc).
- **For David to confirm:** By eye, we have detected *NN* previously unreported streams in this sample (see table 1, Discovery column). The streams we have analyzed have r-band surface brightnesses in the range $25.13 < \mu_r < 27.98\,\mathrm{mag\,arcsec^{-2}}$.
- We have carried out a statistical comparison of $g-r$ colors for the detectable stream and satellite populations in our sample, finding that the detectable stream population is significantly redder on average.
- In systems where a progenitor can be identified with a stream by eye, we find the stream is on average slightly redder than the progenitor.

We suggest that the differences we find between the stream and satellite color distributions may be explained by a combination of selection bias and physical effects. Although our results are statistically significant, a larger sample is clearly necessary to draw robust conclusions. We therefore provide only a brief summary of possible explanations here, and defer a detailed discussion to future work.

The SAGA survey selects a sample of candidate satellites based on catalog photometry and follows up a subset of these with multi-object fibre spectrographs to obtain redshifts. Extremely compact (M32-like) candidates were not followed up (Geha et al. 2017); although such objects tend to be red, relatively few are known. More significantly, redshifts are more difficult to obtain for candidates with low mean surface brightness, which also tend to be redder. Mao et al. (2021) argue that this redshift incompleteness is a weak effect that does not significantly bias the distribution of star formation rates (hence colours) in the spectroscopic sample. However, the completeness of the initial target catalog may also be important. Font et al. (2022) explore this issue in detail through comparison to the ARTEMIS suite of cosmological simulations. They suggest that the photometric SAGA candidate sample may have a significant bias against low surface brightness satellites, and that this bias has a much stronger effect on the resulting colour distribution. Comparing to a separate survey of satellites in the Local Volume **Cite: carlsten 2021?**, the find evidence that fainter galaxies in SAGA are biased towards bluer colors.

However, even with the small sample of stream colors presently available, we find at least two reasons to consider physical explanations for the colour differences in addition to selection effects. First, Font et al. (2022) find the potential selection bias in SAGA mostly affects the fainter satellite magnitudes ($M_V > -12$), and that the colors of brighter (systematically bluer) satellites are not strongly biased. Although we cannot yet quantify the total luminosity of the streams in our sample, it is likely that readily detectable streams have some bias towards the brighter end of the luminosity function of disrupted progenitors (albeit with large uncertainty due to the wide variety of stream morphology and viewing angle). If we were to compare the streams only to the brighter SAGA satellites, rather than the full sample, the discrepancy in color would be reinforced. Put another way, we detect no streams as blue as the bluest SAGA satellites.

Secondly, the difference in color seen in the small number of stream-progenitor pairs in our sample suggests color gradients may contribute alongside selection-driven differences between the stream and satellite samples (and other population-level effects, such different average ages). Such gradients may be established either before disruption or during the disruption process. A wide variety of physical processes could create gradients through their effects on the relative timescales of gas removal (due to ejection and ram pressure stripping), star formation in residual cold gas, and tidal stripping. At the most basic level, complete tidal disruption will prevent further star formation, leading to the systematic reddening of dynamically older streams. Cosmological simulations are necessary to make quantitative predictions for colour distributions, accounting for the range of satellite star formation histories, gas fractions and orbits, and variations in the satellite accretion rate and disruption efficiency over the range of dark matter halo masses that may correspond to the SAGA sample.

To make further progress, we are currently constructing a larger sample of streams from the DESI Legacy Imaging Surveys, using the techniques presented in this paper. This sample will comprise more than XX galactic systems with streams, drawn from the SAGA host sample. With these data, we will be able to reaffirm our conclusions and carry out meaningful comparisons to physical models of satellite star formation, accretion and disruption.

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