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Host: Danny Horta (Flatiron CCA)
Visit dates: 20 February - 1 March 2024

Motivation

The Milky Way is surrounded by many fainter satellite galaxies that are important laboratories for testing models of cosmology and dark matter. Inferring when these satellites first entered the Milky Way is crucial for characterizing the Milky Way's merger history and studying the physical processes that change dwarf properties, such as star formation. However, theoretical studies that aim to constrain these properties typically only consider intact progenitors (i.e. the mass bound to a dark matter subhalo at present day) to establish relations between, for example, infall time and dynamics (Rocha et al. 2012; Fillingham et al. 2019). As many accreted dwarf galaxies likely have experienced significant mass loss (Shipp et al. 2023), it is important to explore these relationships for a variety of stellar morphologies (intact dwarf, stream, and phase-mixed).

The Auriga project (Grand et al. 2018) is a suite of cosmological zoom simulations of 30 Milky Way-mass haloes, run with a galaxy formation model similar to that used in IllustrisTNG (Pillepich et al. 2018; Springel et al. 2018). In the interest of studying the populations of stellar streams in Auriga, I have worked with a team of simulators to identify all the mergers in Auriga, characterize their stellar masses and morphologies, and calculate their orbital properties (Riley et al., Shipp et al. in prep). The result is a large sample of mergers that can be used to explore relationships between present-day observables ($d_{\rm peri}$, $d_{\rm apo}$, E, L_z, [Fe/H], [Mg/Fe], τ_{90}) and key quantities (M_*, $t_{\rm acc}$) related to the physics of dwarf galaxy formation. Importantly, the Auriga simulations include a subset of 6 haloes run at higher resolution, so we can test any numerical effects due to limited resolution. An example of the resulting merger classifications is shown in Figure 1.

Entering the project, our goals were to explore:

- what present-day observables (orbits, chemical composition) are useful for inferring a satellite's infall time or stellar mass?
- are these correlations applicable across different stellar morphologies (intact dwarf galaxy vs stellar stream)?
- is it possible to construct a model trained on the simulations and apply it to accretion events identified in the real Milky Way?

Research activities and outcomes

After summarizing the vector of observables that I had available for the Auriga mergers, Danny and I spent a fair bit of time discussing the best approach to map those observables onto the infall time $t_{\rm acc}$. While we were originally hoping to use more sophisticated models like neural networks (e.g. Barmentloo & Cautun 2023), we eventually dismissed the idea since the ultimate goal of such a model would be to apply it to the observed Milky Way mergers. Any model trained on the Auriga data would likely "learn" underlying trends that arise from the Auriga galaxy formation model, but these are not guaranteed to exist in the Milky Way[1].

Instead of more sophisticated models, we opted to use a much simpler regression model, which could take linear combinations of observables (even if the observables themselves aren't linear, e.g. $[\rm Fe/H]^2$) and return an estimate for $t_{\rm acc}$. This would be much easier to build a physical intuition, propagate observational uncertainties, and understand when we may be outside of the

[1] As a useful analogy, a neural network trained to predict surgery recovery times given patient data in the UK would not be appropriate to directly apply to patient data in the US, due to differences in the underlying populations of the UK and US.

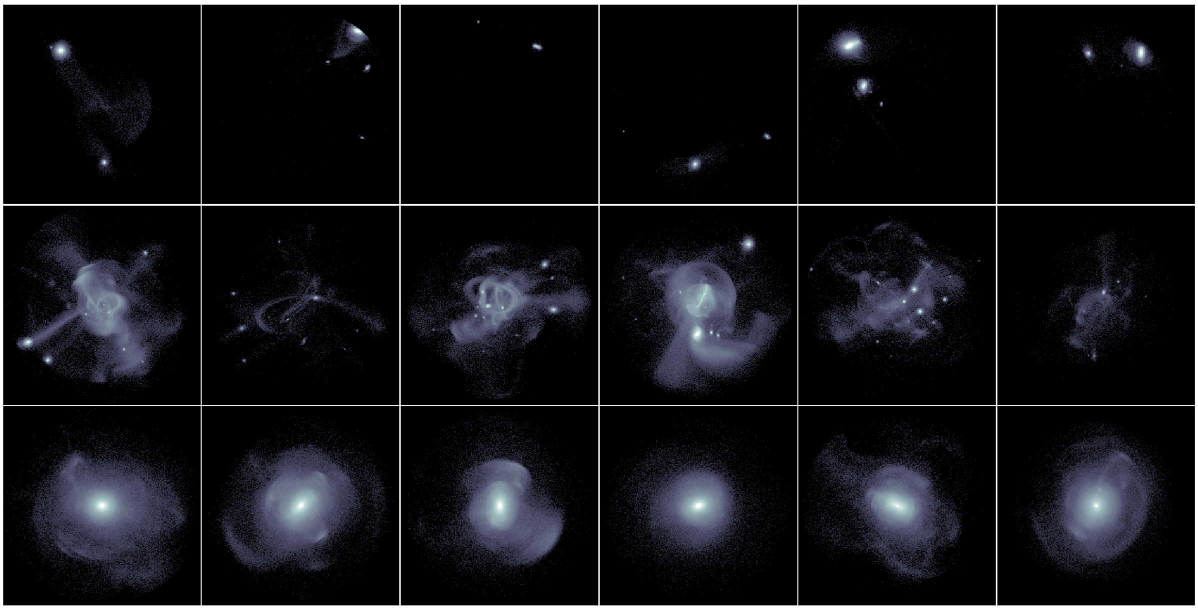

Figure 1: *Six accreted haloes from the Auriga simulation suite, with their merger debris split into intact galaxies (top), stellar streams (middle), and phase-mixed (bottom) morphologies. The color corresponds to the amount of stellar mass in a pixel, logarithmically scaled to improve contrast in low/high-density regions (the color bar is the same for all panels).*

region of parameter space where the model can be trusted. To establish which of observables is most useful for such a model, we looked at scatter plots of each parameter combination (e.g. [Fe/H] vs. $t_{\rm acc}$) for which observables had the most convincing relations. We focus on the lowest resolution Auriga runs (level 4) since this level has the largest sample of simulated haloes and resulting accretion events.

Examples of these plots are shown in Figure 2. Each of these plots shows the distribution of Auriga mergers, with the symbols colored separately for intact dwarf galaxies, stellar streams, and phase-mixed debris. We also fit linear relations and quote mean scatter for each subpopulation (blue, orange, green), as well as considering the whole sample at once (black), though we note that these relationships are rarely linear and should not be taken too seriously. Two key results emerged from analyzing these plots:

1. *There is no strong correlation between accretion time and binding energy.* This is a relationship that has been explored extensively in previous studies (Rocha et al. 2012; Fillingham et al. 2019; Barmentloo & Cautun 2023), though only considering only the bound component of subhaloes that remain at $z = 0$. It is not clear if this is an issue with our data sample (eg calculating the binding energy may require a more sophisticated approach than simply taking the mean of the particle energies) or if this relationship breaks down when considering only luminous mergers and/or including mergers that have fully disrupted.

2. *There is a clear link between accretion time, stellar mass, age (t_{90}), [Fe/H], and [Mg/Fe].* This likely is an imprint of environmental quenching due to ram pressure effects as galaxies accrete onto the larger host, a physical process that has already been explored in Auriga (Simpson et al. 2018). While the stellar mass-[Fe/H] relation has been explored as a function of time in simulations (eg moving from snapshot to snapshot as in Ma et al. 2016), we are not aware of a version of the analysis that collapses the information to $z = 0$ observables, as has been done for observations of Milky Way mergers (Naidu et al. 2022).

Both of these results are exciting enough to merit further investigation, and if they held up under further scrutiny then each would justify a publication. We plan to continue this analysis

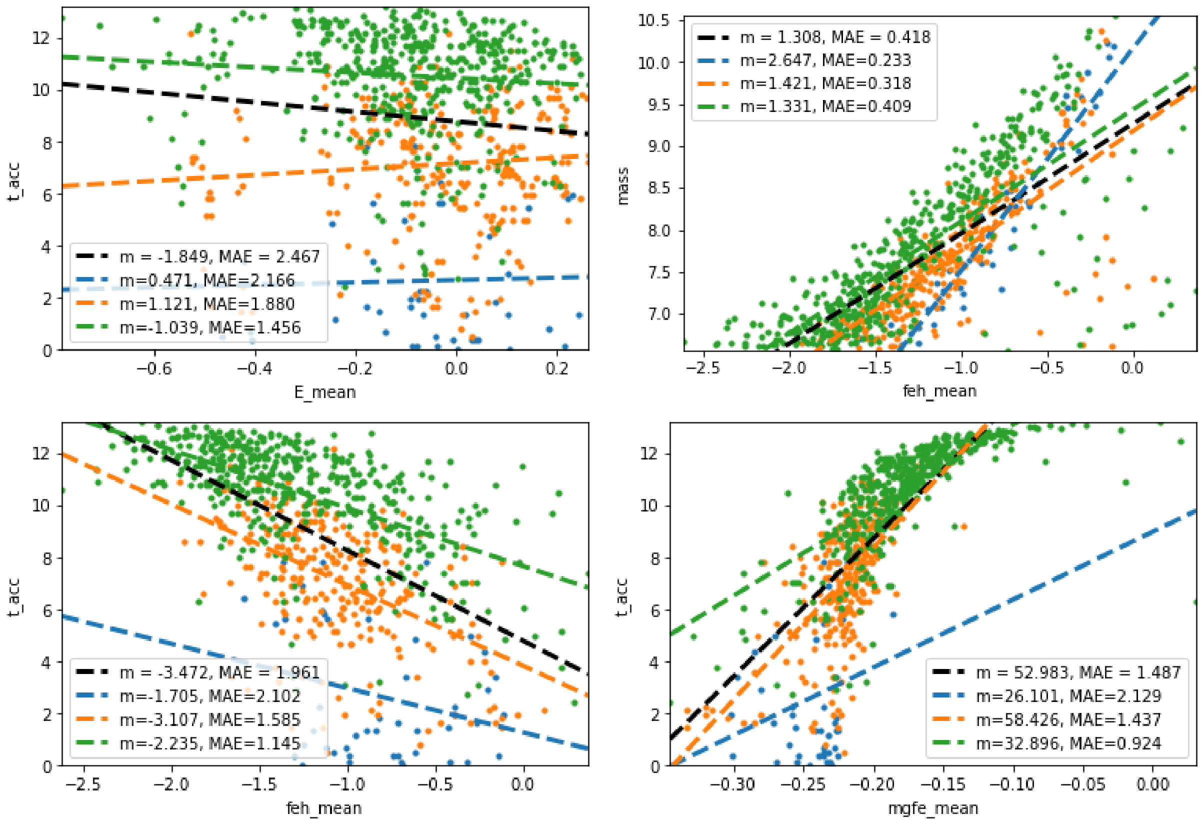

Figure 2: *Example relations between observable quantities and accretion time t_{acc} and stellar mass using Auriga simulation data, splitting mergers into intact galaxies (blue), streams (orange), and phase-mixed (green). Previous studies have reported a strong relation between accretion time and binding energy (Rocha et al. 2012; Fillingham et al. 2019) that is not readily apparent in the Auriga data (top left). We do find a relationship across t_{acc}, stellar mass, age, [Fe/H], and [Mg/Fe] (bottom and top-right panels), likely resulting from the environmental quenching as satellites fall into the host halo.*

in the following year (likely not resuming until the fall of 2024, given other ongoing research projects that I need to finish up) with at least one paper expected in the first half of 2025.

Other interactions

In addition to the research activities described above, I had the opportunity to present (and gain useful feedback on) my work on the Auriga stellar streams at the Local Universe group meeting. I also interacted with several scientists, both CCA-affiliated and external, during my visit. In particular, the serendipitous overlap between my visit and the XMC "Milky Clouds Over Manhattan" workshop the week of 26 February dramatically enhanced the number of these interactions.

- Arpit Arora: Arpit and I discussed his work on the anisotropic distribution of dark matter subhaloes due to the recent accretion of the LMC, as well as the acceptable ways to select Milky Way "analogues" from cosmological simulations.

- Rachel Beaton: Rachel and I discussed the Roman Space Telescope's expected capabilities for proper motion measurements and other interesting Local Group science. We also touched on the political realities and possible timelines for an all-sky, two-epoch survey with Roman.

- Alyson Brooks: Alyson, Nora Shipp, and I had a lengthy discussion on identifying stellar streams in cosmological simulations, the possible numerical and galaxy formation physics reasons for differences between FIRE and Auriga streams, and the nuances of making comparisons between simulated satellite population data and the real Milky Way satellites. We agreed on the importance of adding DC Justice League to the list of simulation projects that have analyzed disrupting systems, with Nora working closely with a PhD student on that effort.

- Richard Brooks: Richard and I discussed his work characterizing the impact of the LMC on simulated stellar streams with different initial conditions. Along with Nico Garavito-Camargo, we agreed that distant stellar streams could be useful for measuring the reflex motion of the MW-LMC interaction in a way that isn't affected by substructure in the Milky Way halo. I encouraged them to pursue this application during Richard's CCA Pre-Doctoral Fellowship.

- Vedant Chandra: Vedant and I discussed his work identifying distant stellar streams in the Gaia and H3 data, as well as my cautionary tale of interpreting the velocity dipoles in the FIRE stellar haloes in relation to the MW-LMC interaction.

- Emily Cunningham: Emily and I set up a plan for finishing our paper on the velocity dipole in FIRE stellar haloes. In addition, we also discussed the opportunities and pitfalls of identifying analogues of observed stellar streams (e.g. Sagittarius) in cosmological simulations. I also asked her for advice on applying for the Hubble Fellowship and selecting potential host institutions.

- Nico Garavito-Camargo: Nico and I discussed his work with the orbital poles of halo tracers in FIRE simulations in response to an LMC-like massive accretion. We agreed that this effect helps alleviate the tension in the observed satellite plane around the Milky Way, but that in detail it's possible that the stellar haloes in FIRE have a different orbital distribution than the Milky Way, and that the Auriga streams could be a useful testbed for this.

- Óscar Jiménez-Arranz: Oscar and I discussed his suite of N-body simulations of MW-LMC interactions and how much of his results he expects to remain the same if he added gas physics. He also shared his code for making amazing RGB images of simulated systems, which I plan to apply to the mock catalogs created from the Auriga galaxies.

- Kathryn Johnston: Kathryn and I discussed my results with the Auriga stellar streams, along with potential pitfalls of making close comparisons between simulations and the real Milky Way. I also asked her for advice on applying for fellowships in the US and UK.

- Nitya Kallivayalil: Nitya and I discussed the exciting discoveries of dwarf galaxy member stars at large on-sky separations. I encouraged her to consider following these claimed detections up with space-based observations to obtain proper motions that would help distinguish between the "disrupting progenitor" and "accreted dwarf stellar halo" interpretations of these observations.

- Dhanesh Krishnarao: Dhanesh and I discussed our experiences navigating large scientific collaborations and how to balance the demands of collaboration with the need to produce first-author papers. He also shared his experience as a tenure track faculty member at a liberal arts college.

- Madeline Lucey: Madeline and I discussed differences between the accreted populations in Auriga and FIRE simulations, and how these could impact her analysis of the inner accreted haloes in FIRE. I also peppered her with questions about the low-metallicity tail of the inner Milky Way and her work measuring the pattern speed of the Milky Way bar.

- Cecilia Mateu: Cecilia and I had a several chats on constructing a catalog of observed streams and dealing with heterogeneous stream discovery and validation techniques in the literature. She also provided useful guidance on how to select RRL tracers in mock catalogs based on the PARSEC stellar evolution code, which I've now incorporated into my procedure for building mock catalogs for the DESI Milky Way Survey.

- Jacob Nibauer: Jacob and I discussed his work modeling subhalo interactions with stellar streams in the linear approximation regime, and how to incorporate realistic measurement errors into his modeling.

- David Nidever: David and his student Slater Oden presented some very interesting work suggesting a detection of the LMC's accreted stellar halo. We discussed the implications of this and agreed that I should try expanding my plan to model accreted stellar haloes around dwarf galaxies to more massive systems like the LMC.

- Ekta Patel: Ekta and I discussed her technique for modeling the orbits of Milky Way satellites in the presence of a massive LMC, including how the inferred satellite orbital distribution could be impacted by observational bias. I also asked her for advice on applying for the Hubble Fellowship and selecting potential host institutions.

- Adrian Price-Whelan: Adrian and I had a brief chat recapping the remaining work for publishing our project on velocity dipoles in the FIRE stellar haloes, as well as our hopes for the Streams24 conference that I am organizing in August 2024 in Durham. He also provided useful input on my preliminary results on the effect of modeling correlations in the Milky Way's rotation curve data (Oman & Riley 2024), including reporting the enclosed mass within 20 kpc in our summary Table. Following a lively Q&A session during the XMC workshop, we also established a bet on how many distant stellar streams will be discovered in the ten-year LSST data.

- Nora Shipp: while Nora and I are close collaborators and have weekly dedicated telecons for the Auriga streams project, we also had several in-person discussions during my visit, including live iterating on final plots for Auriga Streams Papers I and II, sketching a roadmap to performing mock LSST observations of the Auriga streams, and how the Auriga streams could fit into ongoing analyses within the LSST-DESC collaboration in preparation for LSST Year 1 data.

- Eugene Vasiliev: Eugene and I mainly discussed various sources of disequilibrium in the Milky Way (the LMC, Sagittarius) and their impact on efforts to measure the mass of the Milky Way. In particular, I showed him preliminary results on the effect of modeling correlations in the Milky Way's rotation curve data (Oman & Riley 2024).

Acknowledgements

This work was supported by collaborative visits funded by the Cosmology and Astroparticle Student and Postdoc Exchange Network (CASPEN). AHR is supported by a Research Fellowship from the Royal Commission for the Exhibition of 1851.

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