<u>The Outskirts of Dark Matter Halos in Simulations and Observations</u>

Intellectual Merit How do you study something you cannot see? Dark matter (DM) is responsible for shaping the large-scale structure of the universe we see today, comprising 80% of all matter. Decades of direct and indirect searches for annihilation radiation have not yielded any signals. In order to study DM astrophysically, we must use the luminous parts of the universe — the galaxies and galaxy clusters that reside inside DM halos — as tracers. The DM halo relationship is cleanest near the outskirts of these structures, where non-gravitational physics, such as AGN feedback, have the least effect. While difficult to observe due to their low density, new and upcoming advancements in instrumentation are detecting observational tracers in halo outskirts for the very first time. Subsequent measurements of DM halo mass and dynamical quantities, such as accretion rate, will constrain not only large-scale structure but also the nature of the DM particle itself.

My project explores the outskirts of both individual galaxies and galaxy clusters: two structures at different cosmological scales but subject to fundamentally similar dynamics. Starting on the scale of galaxies, the brightest cluster galaxies (or BCGs) have extended faint stellar halos that are now thought to have physically significant edges [1]. Moreover, in recent optical images from the Hyper Suprime-Cam Subaru Strategic Program (HSC survey), it has been shown that the stellar mass in the outskirts (10-100kpc radii) of low-redshift BCGs is an excellent proxy for DM halo mass [2]. The outskirts of these massive galaxies are dominated by stars accreted during mergers with previous satellite galaxies and thus provide an estimate of "historical richness" for their DM halos. While promising for its potential of measuring DM halo mass, this result leads to more questions: Why is the 10-100kpc region significant? Could an even tighter relationship to DM mass exist with stellar profiles past 100kpc?

On a larger scale, the outskirts of galaxy *clusters* (>1Mpc) also provide a laboratory for the effects of DM. At these distances, dark matter particles turn around at their apocenter, called the splashback radius, the location of which depends on the halo's mass accretion rate (MAR) [3, 4]. Recent simulation work suggests this radius coincides with an analogous "stellar splashback" radius of the cluster's stellar distribution (or intracluster light, ICL), which would also vary with MAR and reveal intriguing DM halo dynamics [1]. The small sample and use of zoom-in simulations in this study warrants a followup investigation with cosmological box simulations and a larger sample. How observable this ICL edge will be with future instruments is also unclear and requires further modeling.

There are many other unexplored phenomena at these cluster outskirts, not only in DM but in the hydrodynamics of gas. In particular, an accretion shock must be produced when cold gas falls into a halo and experiences a drastic jump in temperature. According to the self-similar collapse model [5, 6], the radius at which this shock appears should be almost identical to the cluster's splashback radius [7], making it another potential observational tracer of DM. However, the model has not held up in simulations, in which the shock radius has been found to be 20-100% larger than the splashback radius [8]. This disagreement is a fundamental theoretical gap that needs to be understood to interpret current high-resolution observations of the Sunyaev-Zeldovich effect in clusters (from the South Pole Telescope and Atacama Cosmology Telescope) as well as near-future radio observations of accretion shocks.

Cosmological simulations offer the opportunity to understand the connections between baryonic physics and underlying DM halos in order to both interpret observations and make predictions out to halo radii we cannot yet observe. While many processes in simulations are implemented via subgrid models, the processes in halo outskirts are mostly-first principle physics producible even with these limited modeling conditions. I will use cosmological simulations of dark matter and galaxies including the large volume cosmological box simulation suite Illustris-TNG (TNG) [9]. **I propose to use TNG to investigate multiple baryonic physics phenomena at the outskirts of galaxies and of galaxy clusters as potential tracers of dark matter halo properties.** My project consists of 3 scientific goals:

1. Develop robust techniques to measure BCG light profiles out to large radii to find optimal estimators of DM halo mass
2. Test the connection between ICL edges and splashback radius
3. Analyze the relationship between the accretion shock radius and splashback radius

1. Galaxy Stellar Outskirts and DM Halo Mass The HSC survey is a major step in observers' ability to optically image BCG outskirts out to 100kpc given its high-quality seeing conditions and a depth 3-4 magnitudes deeper than the SDSS. In collaboration with the HSC team, I will use these data to develop a new technique for extrapolating stellar mass profiles of high-mass BCGs beyond their observable radius by testing them against a sample of simulated, mock-observed TNG galaxies of similar mass.

A crucial consideration in simulation-observation comparisons is how to recreate the conditions used by observers. To achieve this science, we need to overcome technical hurdles. For example, the file ordering of the TNG output data is by friends-of-friends groups, such that overlapping groups could lead to one group missing particles near its outskirts. Forgoing this data organization to insure all particles are accounted for makes extracting complete profiles out to large radii in large simulations is a non-trivial task. I recently implemented a function in a simulation-extraction software, Hydrotools, that overcomes this challenge and allows users to extract all particles within a given radius. This function lays the foundation for any project relying on large-scale radial profiles.

2. ICL and Mass Accretion Rate Satellites fall into a halo with various velocities, orientations, and internal energies, so it is not immediately clear that disrupted stars in the ICL are faithful tracers of the DM halo potential. I will use Hydrotools to extract complete stellar and DM profiles from halos in TNG to investigate this connection. The splashback radius is signified by a caustic in the DM density profile where particles pile up after their first orbit, so the "stellar splashback radius" can be found analogously in the stellar density profile. I will calculate the difference between these radii and their different correlations with MAR for a sample of various mass halos, predicting the use of the ICL as a DM halo tracer.

3. Shock and Splashback Radii While TNG does not output shock surfaces specifically, we can instead detect a sharp drop in gas entropy profiles to signify the accretion shock radius. I will analyze the relationship between the shock and splashback radii in massive halos over different stages of cluster merger events, using complete gas and DM profiles. These results will provide context to interpret the rapidly growing amount of Sunyaev–Zeldovich, and soon radio, accretion shock observations.

Future Directions The outskirts of galaxies and of galaxy clusters are a clear next place to look for potential tracers of DM halos. Upcoming instruments and surveys will revolutionize our constraints on DM features such as the splashback radius. Moreover, the low surface brightness of BCG and ICL outskirts are already detectable with the HSC survey and will be even more so with the upcoming Vera. C. Rubin Observatory and the Nancy Grace Roman Space Telescope. In the radio regime, the Square Kilometer Array (SKA) will vastly increase the number and resolution of observed accretion shocks. However, to interpret any of these observations we need to improve our theoretical understanding. My project will build off of current observational work and provide the foundation for interpreting future data.

Broader Impacts I will continue my work to limit barriers for underrepresented minorities (URM) in astronomy. Particularly, I will use the remainder of my term serving on the AAS SMGA (sexual orientation and gender minorities in astronomy) committee to develop a mentorship program for LGBTQ+ early career astronomers. This program will match graduate students and postdocs with more experienced mentors who share a LGBTQ+ identity. Mentors will guide mentees through navigating the field, especially challenges specific to LBGTQ+ individuals in the workplace. I will also continue to co-lead the BANG! (Better Astronomy for the Next Generation) seminar series in my department which covers alternate career paths and EDI issues in Astronomy. I will focus on planning seminar sessions covering previously under addressed topics, such as accessible teaching strategies and equitable workplace practices. Finally, I will continue to work with the GRADMAP (Graduate resources for advancing diversity with Maryland astronomy and physics) team to provide external research experiences for students at minority serving institutions by teaching workshops in career skills and serving as a summer research mentor.

[1] Deason et al (2020) [2] Huang et al (2021) [3] Diemer & Kravtsov (2014) [4] Adhikari et al (2014) [5] Bertshinger et al (1985) [6] Shi et al (2016a) [7] Shi et al (2016b) [8] Aung et al (2021) [9] Pillepich et al (2018)