The tidal evolution of dark matter substructure: a data-driven semi-analytical model and its applications to small-scale cosmology

Dissertation Prospectus
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Accurately predicting the abundance and structural evolution of dark matter subhaloes is crucial for understanding galaxy formation, large-scale structure, and constraining the nature of dark matter. Due to the nonlinear nature of subhalo evolution, cosmological N-body simulations remain its primary method of investigation. Subhaloes in such simulations have recently been shown to still be heavily impacted by artificial disruption, diminishing the information content (at small scales) of the simulations and all derivative semi-analytical models calibrated against them. Our recent release of the DASH library of high-resolution, idealized simulations of the tidal evolution of subhaloes (unhindered by numerical over-merging due to discreteness noise or force softening) enables a more accurate calibration of such semi-analytical treatments of dark matter substructure evolution. We have since used DASH to calibrate a highly accurate, simply parametrized empirical model of the evolved subhalo density profile (ESHDP), which captures the impact of tidal heating and stripping. By combining this ESHDP model with a physically motivated prescription for the subhalo mass stripping rate, we have introduced a state-of-the-art model of the mass evolution of individual subhaloes. This model has been calibrated to reproduce the mass trajectories of subhaloes in the DASH simulations, each of which follow a live N-body subhalo as it orbits within a static host halo whose potential is described by the NFW density profile. We have since incorporated this treatment of the subhalo internal structure and mass evolution into the recently released SatGen semi-analytical model. SatGen combines (i) analytical halo merger trees, (ii) a recipe for initial subhalo orbits at infall, (iii) an orbit integrator (which captures dynamical friction), and (iv) our DASH-calibrated tidal evolution model in order to ultimately capture the build-up and evolution of populations of dark matter substructure. In the proposed dissertation, we will employ the DASH-calibrated SatGen framework to generate independent predictions for key quantities in small-scale cosmology, including the evolved subhalo mass function, subhalo radial abundance, and the substructure mass fraction and its dependence on host halo mass. We also propose to study substructure segregation as well as the impact of baryonic discs on subhalo abundance, potentially setting updated bounds on the dark matter annihilation boost factor and the abundance of satellite galaxies in the Milky Way. This work will serve as a powerful check on the results of cosmological simulations, which may still be impaired by artificial subhalo disruption, and has the potential to constrain the nature of dark matter.

1 Introduction

The standard Λ cold dark matter (ΛCDM) cosmological model predicts that structure forms as the consequence of primordial dark matter overdensities that collapse to form self-bound haloes. Smaller perturbations collapse earlier and merge to form larger haloes, resulting in a hierarchical halo assembly process that spans all mass scales. By studying halo evolution via cosmological N-body simulations, it is clear that the tightly bound central regions of smaller haloes survive the merger process and persist within their host as subhaloes. Neglecting the impact of baryonic physics, this merger process is self-similar due to the scale-free nature of gravitational collapse and the ΛCDM power spectrum, ultimately resulting in an entire hierarchy of substructure, where subhaloes themselves host sub-subhaloes, and so on all the way down (Tormen et al., 1997; Gao et al., 2004; Kravtsov et al., 2004). Orbiting subhaloes persist within a treacherous environment plagued by disruptive forces, fighting for their survival against dynamical friction, tidal stripping and impulsive heating from their host, as well as harassment by fellow subhaloes (e.g., Mo et al., 2010).

The population statistics of dark matter (DM) substructure are incredibly rich in detail, most often summarized in terms of subhalo mass functions (SHMFs) and radial abundance profiles; these summary statistics depend heavily on the underlying particle nature of DM. For example, the free-streaming cutoff scale, set by the DM thermal velocity, determines the minimum halo mass (e.g., Knebe et al., 2008; Lovell et al., 2014; Colín et al., 2015; Bose et al., 2017), non-negligible DM self-interactions would suppress the formation of cuspy inner halo density profiles (e.g., Burkert, 2000; Vogelsberger et al., 2012; Rocha et al., 2013), and an ultra-light bosonic DM particle would result in a dense solitonic halo core that undergoes a confined random walk and is surrounded by a turbulent environment filled with quasi-subhaloes (e.g., Schive et al., 2014, 2016, 2020). The detection of observational signatures of dark matter substructure without associated galaxies would be a smoking gun signal for the existence of dark matter. Thus, many observational searches are underway, leveraging gravitational lensing (e.g., Dalal & Kochanek, 2002; Keeton & Moustakas, 2009; Vegetti et al., 2014; Shu et al., 2015; Hezaveh et al., 2016; Gilman et al., 2020), indirect detection via DM annihilation to γ-rays or decay signals (e.g., Strigari et al., 2007; Pieri et al., 2008; Hayashi et al., 2016; Hiroshima et al., 2018; Delos, 2019; Facchinetti et al., 2020; Rico, 2020), gaps in stellar streams (e.g., Carlberg, 2012; Ngan & Carlberg, 2014; Erkal et al., 2016; Bonaca et al., 2020; Necib et al., 2020), among other approaches. Since satellite galaxies are inferred to live within subhaloes, with their respective properties related via the galaxy-halo connection, DM substructure statistics are intimately connected to satellite galaxy abundances (e.g., Vale & Ostriker, 2006; Hearin et al., 2013; Behroozi et al., 2013; Newton et al., 2018; Nadler et al., 2019, 2020a,b) and thus can be used to constrain cosmology through their impact on small-scale clustering statistics (e.g., Benson et al., 2001; Berlind et al., 2003; Kravtsov et al., 2004; Lange et al., 2019; van den Bosch et al., 2019). Clearly, accurately modeling the evolution of DM subhalo populations is a prerequisite for their use as a cosmological probe and as a tool to study the particle nature of dark matter. Unfortunately, since the evolution of DM substructure is highly non-linear, modeling all but the most idealized circumstances have proven analytically intractable. Thus, to date, cosmological N-body simulations have been the most successful avenue for studying DM halo structure evolution, clustering, and abundance.

In recent years, cosmological simulations have successfully and repeatedly passed an important convergence test: as resolution is varied, the SHMFs remain in agreement above the 50–100 particle limit (e.g., Springel et al., 2008; Onions et al., 2012; Knebe et al., 2013; van den Bosch & Jiang, 2016; Griffen et al., 2016; Ludlow et al., 2019). While this is promising, the physical correctness of cosmological simulations is not guaranteed by the convergence of mass functions alone. Using the state-of-the-art *Bolshoi* simulation (Klypin et al., 2011), van den Bosch (2017) found that the evolved SHMF of surviving subhaloes looks identical to the SHMF of disrupted subhaloes, noting that total subhalo disruption is prevalent. The inferred disruption rates from various studies are extremely high, with roughly 55-65% (90%) of subhaloes accreted at $z = 1$ (2) being disrupted by present day (Han et al., 2016; Jiang & van den Bosch, 2017; van den Bosch, 2017). Van den Bosch (2017) splits disruption into several branches based on the properties of the subhalo at the time of disruption, concluding that approximately 80% of subhalo disruption is most likely numerical in nature. In an early, influential study on subhalo tidal evolution, Hayashi et al. (2003) argued that it is possible for a subhalo remnant to have positive binding energy, and thus become capable of spontaneous disruption, if its mass profile becomes instantaneously truncated down to a sufficiently small radius (within which roughly 5–10% of the subhalo mass lies). Motivated by this analysis, subsequent works have incorporated physical disruption via tidal stripping and heating into their models or used such an argument as a justification for their results (Zentner & Bullock, 2003; Taylor & Babul, 2004; Klypin et al., 2015; Garrison-Kimmel et al., 2017). Recently, however, van den Bosch et al. (2018) demonstrated that the boundedness of a subhalo remnant does not depend solely on the total binding energy, but rather on the radial distribution of the binding energies of the constituent particles. In fact, by using idealized, simulations with sufficiently high resolution, van den Bosch et al. (2018) showed that it is possible for a self-bound remnant to survive even once 99.9% of the mass has been stripped. More broadly, the study used analytical arguments to show that neither tidal heating nor tidal stripping alone are capable of causing complete physical disruption of cuspy, CDM subhaloes (consistent with earlier work by Peñarrubia et al., 2010). As a follow-up, van den Bosch & Ogiya (2018) ran a suite of idealized numerical simulations, concluding that disruption of N-body subhaloes in cosmological simulations is largely numerical in nature and can be largely attributed to (i) discreteness noise caused by insufficient particle resolution and (ii) inadequate softening of gravitational forces.

If the majority of subhalo disruption in cosmological simulations is indeed numerical, the implications for small-scale cosmology and astrophysics are profound. For example, a disruption-driven reduction in subhalo statistics would result in systematic biases in predictions from subhalo abundance matching (e.g., Vale & Ostriker, 2006; Conroy et al., 2006; Guo et al., 2010; Hearin et al., 2013; Chaves-Montero et al., 2016). Semi-analytical models of galaxy and dark matter substructure evolution (e.g., Taylor & Babul, 2001; Peñarrubia & Benson, 2005; Zentner et al., 2005; Diemand et al., 2007; Kampakoglou & Benson, 2007; Gan et al., 2010; Pullen et al., 2014; Jiang & van den Bosch, 2016; Jiang et al., 2020; Yang et al., 2020) have historically been calibrated to reproduce the results of cosmological simulations, and thus end up having inherited any systematic issues present in such simulations. Jiang & van den Bosch (2016) built a semi-analytical model aimed at reproducing the SHMFs of haloes from *Bolshoi*. They were able to successfully match the evolved SHMF by simply tuning their orbit-averaged mass-loss rate; however, in order to reproduce the unevolved SHMF of *Bolshoi* subhaloes that survive to the present day (i.e., only excluding subhaloes that have been disrupted), the authors introduced a disruption mechanism that models the statistical properties of *Bolshoi* subhalo disruption. In the absence of this disruption mechanism, the normalization of the evolved SHMF predictions from Jiang & van den Bosch (2016) is boosted by a factor of two (Green & van den

Bosch, 2019). Hence, depending on the fraction of subhalo disruption in cosmological simulations that is indeed artificial, it remains possible that such simulations (and derivative semi-analytical models) may be underestimating subhalo abundances by up to a factor of two. Such a systematic bias would have serious implications for dark matter indirect detection searches and could help explain the 'galaxy clustering crisis' in subhalo abundance matching (Campbell et al., 2018), since both of these applications, among others, depend heavily on evolved SHMFs from simulations. As long as the effects of artificial disruption remain as an unknown variable in the analysis of cosmological simulations, we will be unable to extract the maximum amount of cosmological and astrophysical information content that will soon be made available in various large upcoming surveys, including DESI, LSST, EUCLID, and WFIRST. Clearly, there is still work to be done towards better understanding the tidal evolution of DM substructure, hence the motivation of the present study.

Recently, we released SatGen (Jiang et al., 2020), a semi-analytical modeling framework for studying galaxy and DM substructure evolution. The core components of the dark matter-only side of the framework (summarized in Fig. 1) include prescriptions for (i) analytical merger trees (Cole et al., 2000; Parkinson et al., 2008; Benson, 2017), from which the internal properties of subhaloes at accretion are derived, (ii) orbital parameter distributions for infalling subhaloes (Zentner et al., 2005; Wetzel, 2011; Jiang et al., 2015, Li et al., in prep.), (iii) the integration of subhalo orbits, including dynamical friction (Chandrasekhar, 1943; Miller et al., 2020), (iv) the evolved subhalo density profile, which captures how the internal structure of the subhalo responds to tidal heating and stripping (e.g., Hayashi et al., 2003; Peñarrubia et al., 2010; Drakos et al., 2017; Green & van den Bosch, 2019), and (v) the instantaneous mass-loss rate, which depends on the structure of both the host- and subhalo in addition to the orbit (e.g., Drakos et al., 2020, this work). In contrast to Jiang & van den Bosch (2016), which followed van den Bosch et al. (2005) by only considering orbit-averaged subhalo evolution, SatGen integrates individual subhalo orbits; such an improvement enables one to correctly account for backsplash haloes (e.g., Ludlow et al., 2009; Diemer, 2020a,b), which, as we will show, can significantly alter the evolved SHMF. The goal of this work is to build a semi-analytical model of substructure evolution that is independent of any tidal evolution-related numerical artifacts that may be present in cosmological simulations. Thus, in Ogiya et al. (2019), we introduced the Dynamical Aspects of SubHaloes (DASH) database, a large library of idealized, high-resolution N-body simulations of the tidal evolution of individual subhaloes. This simulation library has two key strengths: (i) the simulations span a wide range of parameter space, varying the initial orbital parameters and host- and subhalo concentrations and (ii) the live N-body subhaloes satisfy the strict set of convergence criteria laid out in van den Bosch & Ogiya (2018), suppressing numerical artifacts caused by discreteness noise and inadequate force softening. In Green & van den Bosch (2019), we used DASH to calibrate a highly accurate, simply parametrized empirical model of the evolved subhalo density profile (ESHDP), which is unimpeded by numerical artifacts and is applicable to a far wider range of subhalo parameter space than that of previous works (Hayashi et al., 2003; Peñarrubia et al., 2010; Drakos et al., 2017). In this work, we use the results of Green & van den Bosch (2019) as a component in a simple, physically motivated model of the instantaneous mass-loss rate. After calibrating this model to faithfully reproduce the subhalo mass trajectories across the range of DASH simulations, we incorporate it into SatGen, yielding the aforementioned artifact-free semi-analytical model. We use this tool to make predictions for evolved subhalo mass functions, radial abundance profiles, and substructure mass fractions and compare these findings to *Bolshoi* as an independent attempt to quantify the impact of artificial disruption on the abundance of dark matter subhaloes in cosmological simulations.

The previously described work makes up a considerable fraction of the proposed dissertation. Several additional projects are planned, which aim to (i) study subhalo segregation predictions from SatGen in comparison to *Bolshoi*, (ii) quantify the impact of a baryonic disc on the substructure population, (iii) study the predicted halo-to-halo variance in Milky Way-like satellite galaxy populations as a means of testing the remaining viability of warm dark matter models, and (iv) update estimates of the substructure boost factor, which impacts constraints on DM indirect detection analyses. The rest of this prospectus is organized as follows: In Section 2, we lay out a timeline for the past, present, and future development and application of our model, including descriptions of the various sub-projects and corresponding publications. In Section 3, we outline the various collaborations and resources in place that will facilitate the completion of this body of work.

2 Timeline of Projects

The primary goals of our research program are to (i) develop an accurate semi-analytical model of dark matter substructure evolution that is calibrated independently of cosmological simulations (and is thus insensitive to any numerical artifacts that still affect such simulations) and (ii) to use this model to make independent predictions for various quantities significant to small-scale cosmology and efforts to constrain the nature of dark matter. This work has been naturally split into several sub-projects, some of which have already been completed and published whereas others are either in-progress or planned for the near future. Below, we outline the timeline for the past, present, and planned projects that will constitute the proposed dissertation.

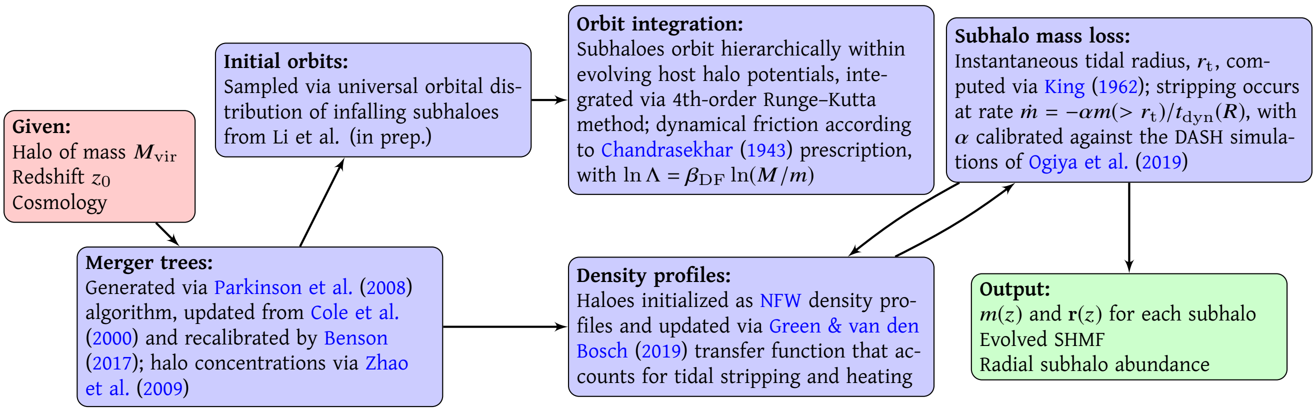

Figure 1: A schematic summary of the SatGen (Jiang et al., 2020) semi-analytical modeling framework for satellite galaxy and dark matter subhalo evolution (focused only on the dark matter-only components). The key advance over previous semi-analytical models is the incorporation of a prescription for the evolved subhalo density profile and instantaneous mass-loss rate calibrated against the DASH simulations (Ogiya et al., 2019) in Green & van den Bosch (2019) and Green et al. (in prep.), respectively.

2019:

- Motivated by van den Bosch et al. (2018) and van den Bosch & Ogiya (2018), we introduced the DASH simulations in Ogiya et al. (2019). These simulations serve as the cornerstone for our subsequent work, as they enable us to calibrate our model of subhalo evolution to reproduce the results of a large set of idealized simulations that are not impacted by artificial subhalo disruption.
- We presented a new, DASH-calibrated prescription for the evolved subhalo density profile (in Green & van den Bosch, 2019) that is both more accurate and more flexible (as it is calibrated over a wide range of host- and subhalo concentrations and initial orbital parameters) than the previous works of Hayashi et al. (2003) and Peñarrubia et al. (2010).

2020:

- In Miller et al. (2020), we investigated the impact of dynamical self-friction, the process by which previously stripped subhalo material exerts a torque in addition to that of the host halo on the subhalo remnant. This additional effect reduces the merging timescale by roughly 10%. In principle, this work could be extended to calibrate a formula for the acceleration felt by the subhalo remnant due to self-friction, which could then be included in the orbit integration of semi-analytical substructure evolution models. However, since self-friction is a second-order effect at most, we neglect it for our subsequent studies.
- In Jiang et al. (2020), we presented the first publicly available release of the SatGen model of dark matter substructure and satellite galaxy evolution. This software library produces full halo merger trees for arbitrary halo mass, observation redshift (z_0), and cosmology. For a sequence of redshifts prior to z_0, SatGen provides the instantaneous masses, concentrations, host-centric phase space coordinates, and parent identifiers for subhaloes of all orders, enabling direct comparison to results from cosmological simulations.
- In Green et al. (in prep.), we have tuned a model of subhalo tidal evolution, which combines the evolved subhalo density profile model of Green & van den Bosch (2019) with a simple, physically-motivated prescription for the subhalo mass-loss rate, to reproduce the mass trajectories of the subhaloes in the DASH simulations. We subsequently incorporated this tidal evolution model into SatGen. We also changed SatGen's routine for sampling initial subhalo orbital parameters at infall to use the state-of-the-art universal infall model of Li et al. (submitted). Using this full framework, we have generated evolved subhalo mass functions, radial subhalo abundance profiles, and substructure mass fractions for a variety of host halo masses at $z = 0$. Using a simple formula from Jiang & van den Bosch (2016) that captures the artificial disruption seen in the *Bolshoi* simulation (Klypin et al., 2011), we find exquisite agreement between our results and *Bolshoi*. In the absence of this disruption mechanism, our model predicts an enhancement in the subhalo mass function normalization and substructure mass fraction, which supports previous concerns about the impact of artificial subhalo disruption on the results of cosmological simulations. We anticipate this publication to be submitted by early October 2020.

2021–2022:

- In van den Bosch et al. (2016), the authors study the segregation of dark matter subhaloes from the *Bolshoi* simulation. The work identifies relationships between segregation indicators (e.g., host-centric radius, projected radius, and binding energy), which capture the relationship between a subhalo and its host, and segregation properties (e.g., m, $m_{\rm acc}$, $m/m_{\rm acc}$, $z_{\rm acc}$, $V_{\rm max}$, $V_{\rm acc}$, among others), which capture internal details about the subhalo and its history. As is clear from the study, there are rich segregation relationships between subhaloes and their hosts, at least as seen in cosmological simulations. For example, subhaloes are strongly segregated by accretion redshift, $z_{\rm acc}$; this is identified via a strong Spearman correlation between $z_{\rm acc}$ and binding energy. After having demonstrated in Green et al. (in prep.) that SatGen accurately reproduces the evolved subhalo mass function and radial abundance profile of *Bolshoi* haloes when the statistical artificial disruption mechanism is enabled, the logical follow-up to this work is to perform a more comprehensive analysis of subhalo segregation as predicted by SatGen. In particular, it will be illuminating to study how well the aggregate of segregation relationships agree between SatGen and *Bolshoi* when the Jiang & van den Bosch (2016) artificial disruption mechanism is applied to the subhalo sample, as well as how significant of an impact disruption has on subhalo segregation. If any stark disagreements between disruption-enabled SatGen and *Bolshoi* are evident, this may provide further insight into how artificial disruption comes about in cosmological simulations and how it could be properly modeled (either physically or via machine learning, as in Nadler et al. 2018), mitigated and eventually corrected for.
- In recent years, various studies have been conducted that attempt to pin down how significantly the presence of a baryonic disc suppresses the level of dark matter substructure in the host halo. In Garrison-Kimmel et al. (2017), the authors compare three cosmological zoom-in simulations of the same Milky Way-like halo from the *Latte* suite: one dark matter-only run, one full baryonic physics run, and one dark matter run that includes an embedded analytical disc potential grown to match that of the disc from the baryonic physics run. They find that relative to the baryonic simulation, the dark matter-only run contains double the subhaloes within 100 kpc of the halo center, and five times the subhaloes within 25 kpc. Importantly, the run with the embedded disc potential reproduces the same level of subhalo depletion as that of the baryonic physics run. Thus, the authors attribute the subhalo depletion to the additional tidal field from the central galaxy.

  However, in another study (Errani et al., 2017), the authors instead use idealized N-body simulations to estimate the impact of a disc potential on a Milky Way-like halo. Using the *Aquarius* simulation (Springel et al., 2008) Aq-A-2 halo merger tree, Errani et al. (2017) evolve each infalling subhalo independently (i.e., ignoring harassment, which has been shown to be insignificant in van den Bosch et al., 2018) as a high-resolution N-body halo within an analytical potential that includes both a growing halo and a Milky Way-like disc. They find that the disc potential suppresses the dark matter substructure by a factor $\lesssim 2$ for subhaloes on orbits that penetrate the disk (i.e., with pericentric radius $\lesssim 20$ kpc).

  Garrison-Kimmel et al. (2017) studies the subhalo radial abundance profile in terms of the instantaneous subhalo radii and Errani et al. (2017) instead uses the orbital pericenter radii; hence, the studies do not present a direct comparison. However, it is clear that the idealized simulation approach by Errani et al. (2017) suggests a far less significant amount of subhalo depletion than the cosmological simulation approach by Garrison-Kimmel et al. (2017). It is possible that this discrepancy arises due to artificial subhalo disruption, which is amplified by the presence of the galactic disc in Garrison-Kimmel et al. (2017). The disc reduces the pericentric radii and increases the tidal forces felt by subhaloes, ultimately driving runaway instabilities that result in artificial disruption.

  In order to test this hypothesis, we can use `OTOO+` (Ogiya et al., 2013) to run additional DASH-like simulations with various embedded baryonic disks. By comparing to these simulations, we can determine if the evolved subhalo density profile model from Green & van den Bosch (2019) and mass evolution model from Green et al. (in prep.) remains valid for subhaloes evolving in an NFW host halo with an embedded disc potential. If this is the case, then our subhalo evolution model does indeed only depend on the local physics of the host potential; on the other hand, we may need to develop a more general model that is able to emulate the impact of a disc on subhalo evolution. We can then use SatGen to generate evolved subhalo mass functions for Milky Way-like haloes both with and without an additional embedded disk. Using the resulting data, we can generate subhalo radial abundance profiles in terms of both the instantaneous radii and the pericentric radii, and compare directly to both Garrison-Kimmel et al. (2017) and Errani et al. (2017). If our hypothesis regarding disc-enhanced artificial disruption is correct, we expect to find results in closer agreement to Errani et al. (2017).
- Recently, Nadler et al. (2020a) carried out a study that used observations of Milky Way satellite galaxies to place very strict bounds on the warm dark matter (WDM), self-interacting dark matter, and fuzzy dark matter models. In Jiang et al. (2020), we use the full SatGen framework, which assumes a model of the galaxy-halo connection to

populate and evolve satellite galaxies within the DM subhaloes, to demonstrate that there is an extreme level of halo-to-halo variance in the satellite galaxy cumulative $v_{\rm max}$ (maximum circular velocity) distribution and radial abundance profile of Milky Way-mass systems. We suspect that a careful consideration of the predicted overall halo-to-halo variance and the scatter in the galaxy-halo connection for low-mass satellites is likely to weaken bounds placed on the particle nature of dark matter reported in the literature.

Using WDM as a case study, we propose the following test. First, we will again run additional DASH-like simulations, this time varying the inner slope of the subhalo density profile in order to test how well the Green & van den Bosch (2019) ESHDP model and Green et al. (in prep.) mass-loss model is able to reproduce subhalo evolution trajectories for non-NFW subhaloes. If necessary, we will pause to develop a more general ESHDP model that works for a range of initial subhalo density profiles and implement this into SatGen. We will use SatGen to generate two, large-sample sets of subhalo and satellite galaxy catalogs for Milky Way-mass systems. The first will be based on analytical merger trees using the standard CDM power spectrum, whereas the second will use a WDM power spectrum (Viel et al., 2005) for a WDM particle mass somewhat below the lower limit of 6.5 keV set by Nadler et al. (2020a). The cuspiness of the initial DM subhalo density profiles at infall will take into account the halo response to baryonic processes (Freundlich et al., 2020); this flexible model has been calibrated to match the halo response seen in both strong-feedback simulations (e.g., FIRE; Hopkins et al., 2018) and weak-feedback simulations (e.g., NIHAO; Wang et al., 2015). Satellite galaxies can be populated and evolved using a model of the galaxy-halo connection currently built into SatGen; however, we may consider collaborating with the authors of UniverseMachine (Behroozi et al., 2019) in order to use their state-of-the-art framework for painting realistic satellite galaxies onto subhaloes. This procedure will enable us to predict the average satellite galaxy luminosity functions and halo-to-halo variance for Milky Way-mass systems in both CDM and WDM. Ultimately, we expect to be able to demonstrate that when considering a realistic level of halo-to-halo variance, WDM models with a WDM particle mass considerably below current lower limits will still be able to reproduce the observed Milky Way satellite galaxy luminosity function.

- The presence of substructure can significantly boost the dark matter annihilation rate within an otherwise smooth host halo. Many previous numerical and analytical works have attempted to pin down the magnitude of this "boost factor", with most interest being directed towards local satellite galaxies and massive galaxy clusters (for a recent review, see Ando et al., 2019). The boost factor is sensitive to (i) the internal density structure of evolved subhaloes, (ii) the minimum subhalo mass (set by the dark matter free-streaming scale), and (iii) the slope and normalization of the evolved subhalo mass function. Using SatGen, we can determine the mass- and redshift-dependence of the subhalo mass function. Additionally, we can use SatGen to establish how the distribution of subhalo bound mass fractions, $m/m_{\rm acc}$, depends on sub-to-host mass ratio, m/M, and host mass, M. The Green & van den Bosch (2019) evolved subhalo density profile is set by $m/m_{\rm acc}$, and thus we can also determine the distribution of evolved subhalo density profiles at fixed m/M and M. In aggregate, we can make simulation-independent predictions for how the boost factor depends on host halo mass, redshift, and minimum subhalo mass and compare to previous studies in the literature. This work can be completed using only data products generated from previous parts of the dissertation and thus should be a relatively simple data analysis project; as such, this offshoot project may turn into an undergraduate research project (for a semester or summer), which will provide SBG with mentorship experience.

3 Collaborations and Resources

The core DASH simulation library has already been generated on the Grace cluster at the Yale Center for Research Computing (Ogiya et al., 2019). All necessary infrastructure is already in place on the Grace cluster for any additional numerical experiments merited by our planned work, including exploring modified host halo potentials and adding in baryonic disc components. We maintain a collaborative relationship with Go Ogiya, who has developed the OTOO+ GPU-accelerated N-body simulation code used in this work (Ogiya et al., 2013).

Much of the proposed work utilizes a modified version of the SatGen semi-analytical model (Jiang et al., 2020), which is publicly available online[1] and under active development by Dr. Fangzhou Jiang (post-doctoral fellow at Caltech) and SBG. Dr. Jiang is a close collaborator and co-author on our upcoming studies. SBG plans to mentor and collaborate with a Yale undergraduate physics student, Ayelet Kalfus (Yale College '23), on one of the final components of this dissertation work, which is aimed at quantifying the dark matter annihilation boost factor based on results from the SatGen model.

In parallel to the work described in the previous sections, SBG is also involved in several other collaborations. Alongside Prof. Jessi Cisewski-Kehe (UW Madison), we are using topological data analysis, specifically persistent homology, as a framework to develop test statistics for hypothesis testing that can be employed to discriminate between various cosmological models (e.g., WDM vs. CDM). Additionally, SBG is working with Prof. Michelle Ntampaka (STScI) and Prof. Daisuke

[1] https://github.com/shergreen/SatGen

Nagai to employ novel machine learning methods to build a robust estimator of galaxy cluster masses using mock X-ray and Sunyaev–Zel'dovich observations. Lastly, SBG is also working with Prof. Nagai and Han Aung (graduate student at Yale) towards developing a more sophisticated semi-analytical model of the non-thermal pressure support in the intra-cluster medium (see e.g., Green et al., 2020).

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