Astro2020 Science White Paper

Far Reaching Science with Resolved Stellar Populations in the 2020s

Thematic Areas:

- ✓ Formation and Evolution of Compact Objects
- ✓ Cosmology and Fundamental Physics
- ✓ Stars and Stellar Evolution
- ✓ Resolved Stellar Populations and their Environments
- ✓ Galaxy Evolution
- ✓ Multi-Messenger Astronomy and Astrophysics

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Abstract (optional): Resolved stellar population studies can provide some of the most reliable observational constraints affecting a host of astronomy research fields, from the formation of compact object binaries that produce gravitational waves to the nature of dark matter and the evolution of the galaxies that form within its halos. Herein we discuss prospects for significant progress in those areas that we expect will result from projects currently under construction, emphasizing the most impactful capabilities for which to strive in the longer term. In short, assuming LSST and WFIRST are successful, unprecedented spatial resolution deep UV-optical-IR imaging capabilities as well as high-multiplex wide field spectroscopic facilities will be in high demand to probe the many discoveries of these surveys.

Some of the most reliable constraints on the physical processes that dominate the evolution of galaxies come from high-resolution imaging that allows us to measure properties of individual stars in nearby galaxies. Such imaging in the current decade has allowed us to disentangle much of the formation history of the galaxies in the Local Group, as well as those out to about 4 Mpc. This distance limit is mainly because of crowding, as the angular separation between the stars decreases with increasing distance or surface brightness.

The currently-available and under-construction projects for telescopes and instrumentation are not likely to provide significantly better resolution than that of HST at optical wavelengths (0.05″) over arcminute-size fields. Adaptive optics (AO) may provide improvement over very small areas. JWST will provide approximately this resolution in the IR (HST is 0.1″ in the IR), and WFIRST will provide 0.1″ resolution over a very large field. Such wide-field imaging and deep spectroscopy from facilities already planned or under construction for the 2020s (e.g., JWST, WFIRST), will allow detailed studies of entire galaxy halos and their satellite systems, undoubtedly resulting in the discovery of many features containing stellar populations of great interest for transforming our observational constraints on star and galaxy evolution models, as laid out in Table 1.

While much will be achieved with the depth and coverage of LSST as well as the imaging of HST quality over a very large field from WFIRST, these achievements will be largely in the low surface brightness regime where crowding of stars is not the dominant obstacle. A key complement to this capability will be extremely high-resolution imaging and deep spectroscopy to resolve stars in more crowded regions and obtain velocity structures of features discovered by these ambitious surveys.

Stellar Halos as Powerful Probes of Galactic Archaeology

WFIRST will revolutionize our knowledge of the stellar halos of galaxies. These low surface brightness halos provide the strongest known constraints on the accretion histories of galaxies (Bullock & Johnston 2005; Cooper et al. 2010; Pillepich et al. 2014; D'Souza & Bell 2018; Monachesi et al. 2019). Because of this power, much work has been done over the past decade to find these structures in nearby galaxies from the integrated surface brightness (e.g. Dragonfly, Merritt et al. 2016; DGSAT, Javanmardi et al. 2016; Henkel et al. 2017; SMUDGes, Zaritsky et al. 2019; MATLAS, Duc et al. 2015; Fornax Cluster, Iodice et al. 2018; VEGAS, Spavone et al. 2018). These exquisite maps show a variety of substructures and accretion/interaction history for those galaxies, but they do not provide spectral energy distributions or spectra of the individual stars that make up the structures. Deep resolved star/galaxy separation, photometry, and spectroscopy are required to quantify the age and chemical characteristics of the halo structures for detailed comparisons with halo formation models. Such resolved photometry will be possible with WFIRST, but spectroscopy requires multi-objects spectrographs on 30m class telescopes.

Photometry catalogs of resolved stars covering substantial halo areas have so far only been made for a handful of nearby galaxies. Outside of the Local Group, only stars brighter than ~2 magnitudes below the tip of the red giant branch (TRGB) are typically within reach of current resolved stellar population studies (e.g., NGC 891, Ibata et al. 2009, Rejkuba et al. 2009, Mouhcine et al. 2010; NGC 253, Greggio et al. 2014; M81, Okamoto et al 2015; NGC 5128, Crnojević et al. 2016; NGC 4631, Tanaka et al. 2017; GHOSTS survey Monachesi et al. 2016; NGC 3379, Harris et al. 2007, Lee & Jang 2016; NGC 3115, Peacock et al. 2015), but the TRGB provides only weak constraints on the ages and metallicities of the structures and halos. Deeper photometry is required to reach stars more sensitive to population age and metallicity, such as the helium burning red clump/horizontal branch (Rejkuba et al. 2005; Durrell et al. 2010; Rejkuba et al. 2011). The most age-sensitive stars belong to the main sequence turnoff, which is only currently available for the MW and M31 (Newberg et al. 2002; Majewski et al. 2003; Calchi Novati et al. 2005; Ibata et al. 2007; Brown et al. 2008; McConnachie et al. 2009). These studies have provided strong incentive for deeper and more systematic follow-up capabilities, as these structures provide confirmation of the hierarchical galaxy formation paradigm (at least in part; Bell et al. 2008). Such observations have sparked a vigorous theoretical exploration of how galactic assembly can be accurately measured from the remnants of disrupted satellites (e.g., Deason et al 2018, D'Souza & Bell 2018b, Helmi et al 2018, Gallart et al 2019). These insights have tremendous potential, but with relevant observations available for only two galaxies in a single environment, definitive conclusions (e.g. Figure 1) remain out of reach.

As shown in Figure 1, the observed properties of the stellar substructures in galactic halos are associated with fundamental physical quantities: the abundance of tidal debris reflects the recent accretion rate; the physical scales and surface brightnesses reflect the mass and luminosity functions of infalling objects; and the morphologies encode the orbits of accreted objects. Thus, stellar halo substructures offer direct constraints on the history and nature of baryonic and dark matter assembly (Johnston et al. 2008; D'Souza & Bell 2018). Tools for finding and quantifying such structures are successfully being developed (Kado-Fong et al. 2018, Hendel et al. 2019).

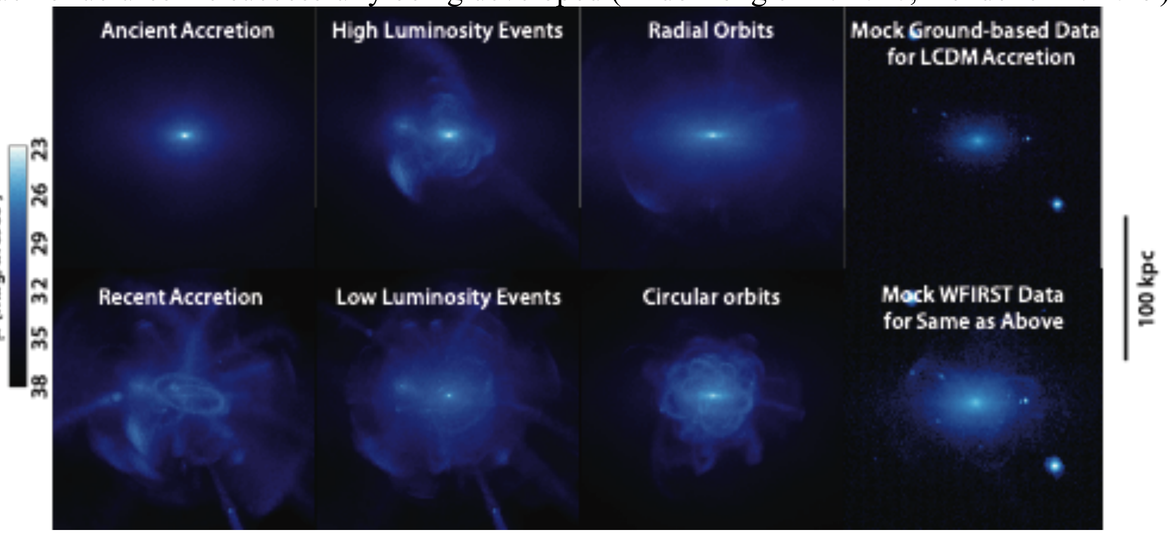

Figure 1: Left Panels: Examples of how halo morphology reflects the history of accretion, for old vs. young accretion events, for high- vs. low-luminosity accreted satellites, and for accretion along radial vs. circular orbits (Johnston et al. 2008). Right Column: Simulated optimal ground-based map (1 hour with Subaru in 0.7″ seeing) of a model halo is shown above a simulated deep, wide-field space-based map, possible with WFIRST, in the 2020s of the same model, which allows exquisite star-galaxy separation to faint magnitudes in low stellar density regions. Even higher resolution will be necessary to probe the more crowded inner and star-forming regions of galaxies. Degree-sized coverage is required to map these areas.

Visible Satellites and Streams as Dark Matter Probes

The ΛCDM model predicts the numbers and masses of sub-halos surrounding higher mass galaxies (Figure 2). These halos should be observable in the form of lower mass satellites around larger galaxies. However, statistical tests of galaxy formation in a ΛCDM context face extensive challenges (see reviews by Weinberg et al. 2013 and Bullock & Boylan-Kolchin 2017). For example, studies of the most luminous MW dwarfs indicate that their central density profiles are flatter and their mean densities are substantially lower than those of simulated subhalos of the same mass (the `core/cusp' and 'too big to fail' problems; Boylan-Kolchin et al. 2011a, 2012).

Driven by these discrepancies observed in the Local Group, significant progress has been made towards reconciling theory and observation. Improved simulations with baryonic and dark matter physics show that some putative dwarf galaxies may never form stars and stay 'dark' (e.g. Kravtsov 2010; Macciò et al. 2010; Pontzen & Governato 2012; Peñarrubia et al. 2012; Bovy & Dvorkin 2013; Arraki et al. 2014, and many others). New searches for dwarf galaxies in nearby groups have resulted in many new dwarf satellite *candidates* to the Milky Way (MW; e.g., DES Collaboration 2015) and several nearby large galaxies (e.g., M81, Chiboucas et al. 2009; M101, Merritt et al. 2014, Bennet et al. 2017 and Danieli et al. 2017; NGC 5485, Merritt et al. 2016; Centaurus, Müller et al 2015, 2017a, Crnojević et al 2016; Leo I, Müller et al. 2018a; NGC 2784, Park et al. 2017; NGC 3175, Kondapally et al. 2018). Many more such satellite candidates, as well as *isolated* ultra faint dwarf galaxies (probing low density environments), will be discovered by LSST and WFIRST. Confirmation, distances, and physical characterization of these ultra-faint galaxy candidates are mostly pending, as follow-up studies are difficult with current capabilities (e.g., Chiboucas et al. 2013, Müller et al. 2018b, Crnojević et al. 2019, Weisz & Boylan-Kolchin 2019).

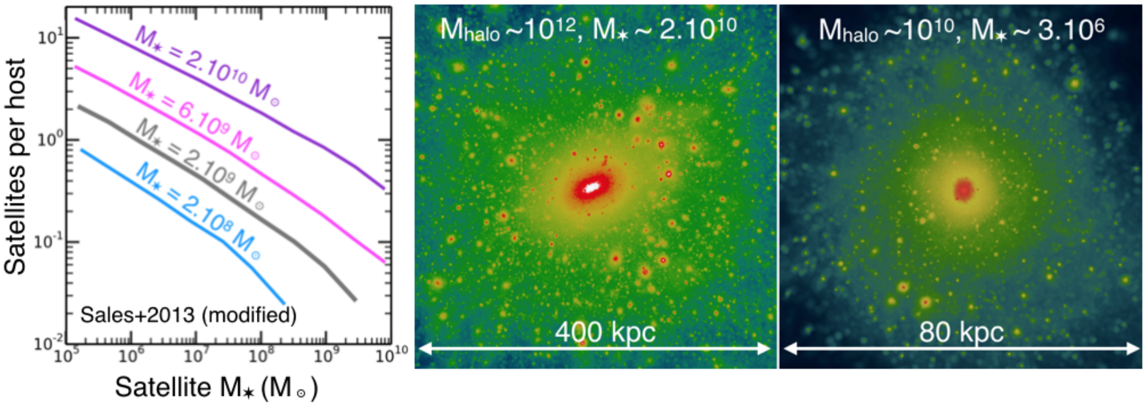

Figure 2: Left: Predicted number of satellite galaxies as a function of stellar mass based on simulations for four different central galaxy masses. These mass functions will vary for different dark matter and galaxy formation models. Technology available in the 2020s (e.g., WFIRST) could potentially measure these mass functions for hundreds of galaxies. Middle and Right: State-of-the-art dark matter simulations of a massive and low-mass galaxy, showing the large number of subhalos predicted down to small mass scales, even at low masses.

In spite of the apparent concurrence between the Local Group and current theory, there is a very real danger that whatever theoretical and/or numerical progress has been made to reconcile the observations in the Local Group has in fact been carefully tuned to a specific environment and formation history that is not necessarily broadly representative (Smercina et al. 2018). The need to push to new environments and to fainter satellite systems beyond the Local Group is therefore acute, if we are to believe that we have truly found the correct solution, rather than just one of many non-unique models of dark matter and galaxy formation. For example, the phase space distribution of some of these dwarfs suggests possible planes of satellites (e.g. Koch & Grebel 2006; McConnachie & Irwin 2006; Tully et al. 2015; Müller et al. 2017a, 2018c), posing a potential problem for ΛCDM. Confirmation of such planes requires systematic follow-up with accurate distances and radial velocity measurements. Future deep imaging with high resolution that can resolve individual stars in dwarf galaxies to ~10 Mpc (i.e., WFIRST) are necessary to obtain secure distances and measure physical properties of satellites (structure, metallicity). Spectroscopy for kinematics for many of them will require 30-40m telescopes.

Furthermore, the dark matter halos of small galaxies are predicted to be populated by a large number of dark matter clumps (see Fig. 2), some of which may host their own faint galaxies. Thus, one of the cleanest observational tests capable of distinguishing collisionless CDM from alternatives (e.g., warm dark matter) is one that answers the following question: do completely dark subhalos exist? The coherence of the debris streams in nearby galaxy halos is a stringent test of the presence of dark matter substructure on much smaller mass scales than the satellite debris itself. Small-scale asymmetries in the gravitational potential lead directly to discontinuities in the debris (Ibata et al. 2002; Johnston et al. 2002; Carlberg 2009), allowing one to make a quantitative connection between the substructure observed along a tidal stream and the underlying mass spectrum of any dark matter mini-halos. For example, the frequency of gaps in the thinner streams from the lowest mass satellites and globular clusters can be used as a test of the presence (or absence!) of dark mini-halos (Yoon et al. 2011; Erkal et al 2016; Bovy et al 2017; Price-Whelan & Bonaca, 2018). Deep resolved photometry (with WFIRST for NIR and star/galaxy separation+LSST for optical) and spectroscopy (with wide-field MOS on >10m telescopes) of these streams will be required to characterize their populations and kinematics.

Stellar Ages: Essential Ingredients for Wide Ranging Questions in Astrophysics

Much of our ability to interpret the light of distant galaxies relies on our present knowledge of stellar structure (including atmospheres) and evolution, and on our ability to extrapolate the evolution inferred in nearby stellar systems to those in distant systems reflecting different age/metallicity regimes. While for some evolutionary phases (e.g. the main sequence, the RGB) extrapolations based on stellar evolution theory appear justified, such assumptions probably do not hold when heavy mass loss processes are involved. One prominent example is the AGB phase of intermediate-to-low mass stars. In this case, present models heavily rely on the populations in the Magellanic Clouds (e.g., Pastorelli et al. 2019). While WFIRST will be capable of widely expanding the number of useful "calibrating samples" (i.e., large areas with preliminary ages from crowding-limited photometry, metallicity, and containing many evolved stars), these samples will demand characterization of atmospheric chemistry (e.g. Boyer et al. 2013, Lebzelter et al. 2018), as well as precise local star formation histories for robust ages to calibrate stellar models -- and, as a consequence, the contribution of these stars to the integrated light and chemical yields in galaxies.

As one can gather from a glance at Table 1, characterizing the ages and metallicities of the stars that make various structures is crucial to allowing quantitative tests of simulations and models of evolution and cosmology. It is widely acknowledged that fitting stellar evolution models to multi-band photometry of resolved stellar populations is the de facto gold standard approach to measuring these characteristics (e.g., Kennicutt & Evans 2012). Obtaining this photometry will be critical to reliably answering all of the questions in Table 1. The power of this technique is remarkable, as the same high resolution photometry can probe the ages of other object types that are of great importance to astrophysics, such as high-mass X-ray binaries (HMXBs; Williams et al. 2018), which are the most likely progenitors of merging stellar mass black holes, the progenitors of supernovae (e.g., Jennings et al. 2014; Williams et al. 2018a), or the AGB stars described above.

The comparable resolution and field of view of HST in the optical and JWST in the NIR will not push these population studies significantly beyond their current limits. The discovery of large samples of remarkable objects will be made with facilities such as WFIRST and LSST, and transformative power beyond the discovery will be enabled with very high resolution imaging by resolving large numbers of the stars that reside in the objects' immediate vicinities. Such transformative resolution may be achieved in the near IR over very small fields of view (few ″ for best resolution) with 30m ground based telescopes equipped with AO systems, but will be achieved over HST-sized fields of view in the UV-Optical with large aperture space telescopes.

Table 1: Key science questions addressed by stellar populations in the 2020s, and the required technology to address them. Blue cells benefit substantially from UV capabilities. Noted distances will provide transformative same increases both in size and environments probed. In all cases, WFIRST will provide the 0.1″ resolution over 0.5° necessary for mapping and discovery.

Question	**Population Measurement**	**Technique**	**Application**	**Technology**
How does the IMF of stars depend on environment?	Resolved Young Star Clusters (UV/Opt)	CMD fitting of cluster main-sequence stars (to 4 Mpc)	Age and luminosity function directly constrain IMF	WFIRST for ID, 0.01″ resolution over few ″ for deep photometry
How do the stellar halos of galaxies form?	Stellar halo structure and kinematics (Opt/NIR)	Stellar maps out to virial radius; Spectroscopy of stars & clusters (to 10 Mpc)	Streams probe interaction history; velocities probe underlying dark matter	WFIRST + 30m MOS for structure maps, populations, and velocities
What cosmology models best match the locations and mass function of dwarf satellites?	Stellar masses of dwarf satellites (Opt/NIR)	Find stellar overdensities, measure their resolved stellar photometry (to 10 Mpc)	Low end satellite mass function distinguishes reionization and dark matter models	WFIRST for ID, 0.01″ resolution over 1′ (LUVOIR) to characterize
What cosmology models best match the ages of dwarf galaxies?	Age distribution of stars in dwarf galaxies (Opt)	Deep CMD fitting of many dwarf galaxies (to 4 Mpc)	Quenching epoch and internal age gradients probe early universe environment	WFIRST for discovery, 0.01″ resolution over 1′ (LUVOIR) for deep photometry
How do stars affect the chemical evolution of galaxies?	Supernova progenitor, HMXB, and AGB star ages (UV/Opt)	CMD fitting of local resolved populations to infer object's age (to 10 Mpc)	Evolution models must match age and metallicity of AGB stars and SN progenitors	WFIRST to ID stars of interest, 0.01″ resolution over arcmin FoV (LUVOIR) for aging
Do completely dark subhaloes exist?	Halo stream shapes (Opt/NIR)	Stellar maps, kinematics of galaxy halos to virial radius (to 10 Mpc)	Subgalactic halos disrupt streams	WFIRST for structure maps, and wide field MOS (0.5°) for kinematics

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