Understanding Galaxy Formation via Near-Infrared Surveys in the 2020s

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☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☒ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract:

Extragalactic astrophysics in the 2020s will enjoy a host of observational facilities that will probe the most fundamental issues of galaxy formation: the history of star and supermassive black hole formation and the connection between galaxies and dark matter. Given the context of these facilities, we argue wide-area photometric and spectroscopic surveys in the near-infrared represent keystones for furthering our understanding of galaxy formation and evolution. Such surveys will allow us to understand better the evolution of galaxy morphology, clustering and environment, star formation, active galactic nuclei, and dark matter substructure over cosmic time. We highlight the critical role that future facilities will play in uncovering these important physics of galaxy formation and evolution.

1 Overview

Studying the formation and evolution of galaxies over cosmic time has continually motivated the development of new space-based observational facilities, including the Hubble Space Telescope (HST) and now James Webb Space Telescope (JWST). With the advent of space-based survey telescopes, the truly new capability of wide-field infrared photometric and spectroscopic surveys of distant galaxies will arrive in the 2020s, complemented by many other critical facilities on the ground and in space (Figure 1). Given the emphasis on baryon acoustic oscillations, weak lensing, and supernova observations for space-based survey telescopes, there will be two overriding goals for understanding and characterizing the power of these surveys for extragalactic astrophysics beyond cosmology:

- How can the near-infrared cosmological surveys be leveraged for extragalactic astrophysics?
- What additional observational programs will be necessary to maximize the science return of space-based survey telescopes for broad extragalactic astrophysics?

While extragalactic discoveries will continue apace over the next few years, a rich portfolio of science programs require wide-area, space-based infrared capabilities and therefore cannot be executed by precursor facilities. Over the last ten years, since the installation of WFC3 on HST and MOSFIRE on Keck, much has been learned about the rest-frame optical and UV properties of thousands of galaxies at redshifts $z > 1$. The CANDELS and UDF12 surveys [1, 2, 3, 4] and the Frontier Fields survey [5] have provided galaxy stellar mass functions to $z \sim 5$, UV luminosity functions to $z \sim 8$, and initial hints of $z > 9$ populations. The MOSDEF survey [6] has conducted the first detailed studies of rest-frame optical line emission in galaxies at $z \sim 2-3$, yielding metallicities and clues to the character of stellar populations in the most distant galaxies yet reachable. These IR studies and other powerful programs conducted by groups around the world have made tangible progress in understanding the evolution of galaxies, but the following critical science questions remain unanswered:

- What is the link between galaxies and their dark-matter halos at $z > 1$?
- How do galaxy star-formation rates and morphology evolve as a function of environment at $1 < z < 7$?
- How does black hole accretion affect the growth of galaxies over this epoch?
- What is the abundance of substructure in dark matter halos outside the Local Group?

These science questions require wide areas to map out large scale structure, high-resolution imaging in the rest-frame optical, and low-background NIR spectroscopy to reach the redshifts of interest. Only a space-based IR survey telescope such as Wide-Field InfraRed Survey Telescope [WFIRST; 7, 8] has the capability to simultaneously address all of these questions.

Precursor facilities have introduced new detector technologies limited to relatively small imaging arrays and, with additional constraints from the telescope optical designs, multi-band space-based IR surveys to date have been limited to < 1000 arcmin^2 in total. Surveys from the ground including DES, HSC, and LSST have and will improve upon these areas, but will lack the unique combination of IR sensitivity, angular resolution, and slitless spectroscopy offered by space-based IR survey telescopes. These features afford an opportunity to connect stellar mass, star formation rates, AGN activity, and morphology to environment through spatial clustering at $z > 1$. The environmental context provided by space-based spectroscopic facilities is a qualitatively new feature

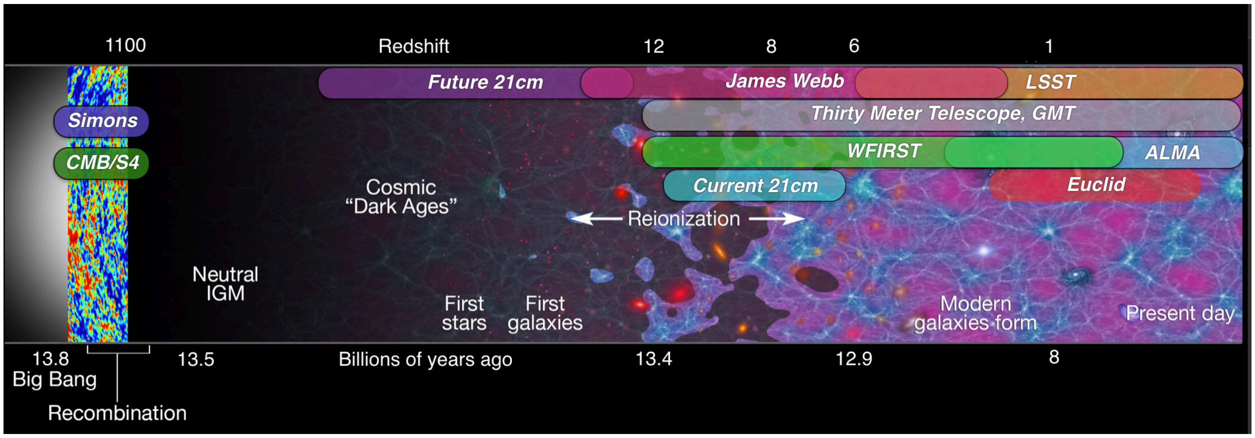

Figure 1: Observational facilities over the next decade. The rich array of ground-based (LSST, ALMA, 21cm, Simons and CMB-S4, TMT/GMT/E-ELT) and space-based (JWST, Euclid, WFIRST) facilities operating during the next decade provide context for conducting extragalactic science programs. Adopted from [13].

for IR surveys, and transcends a simple improvement in number counting statistics. Beyond the context of environment, the areal coverage provided by space-based IR surveys enables additional important capabilities. Rare objects, such as the highest-redshift quasars, massive early galaxy clusters, and bright primordial galaxies, test the limits of our structure formation models [e.g., 9] and provide the ability to probe the intergalactic medium in the distant past [10, 11, 12]. Below, we discuss these critical science areas in extragalactic astrophysics where space-based IR surveys will provide the greatest advances.

2 Galaxy Formation Across Cosmic Environments

Our current understanding of the high-z galaxy population is limited by fundamental assumptions about the relation between galaxy properties and halo mass, with state-of-the-art models formulated on the basis of "abundance matching". While JWST and other future instruments will undoubtedly improve our understanding of these relations, a key test of any galaxy formation model is this galaxy-dark matter connection [14, 15, 16]. Galaxy clustering measurements require both large samples of galaxies and wide-area, contiguous spatial sampling. Space-based IR surveys with spectroscopic capabilities provide ideal platforms for measuring the clustering of bright, high-redshift galaxies and hence their dark matter halo environments (see Figure 2). Further, weak lensing allows us to connect galaxies with halo mass and local dark matter environments through the wide-area, high-resolution IR datasets [17]. These efforts will enable models to pin down the assembly of bright galaxies over cosmic time and hence the process of star formation within these environments.

How could a space-based IR surveys be used to address these science issues? We can use WFIRST's capabilities and our current knowledge of the evolving galaxy luminosity function [e.g., 18] to provide some firm numbers. While the bright end of the luminosity function ($m < 26.7$AB) will be exquisitely captured by the WFIRST High Latitude Survey (HLS), medium-depth surveys with $10\mathrm{deg}^2$ area to a depth of $m \sim 28.5$AB would probe a significantly different luminosity regime at $z \sim 7-8$ and provide significantly better image quality for morphological studies at

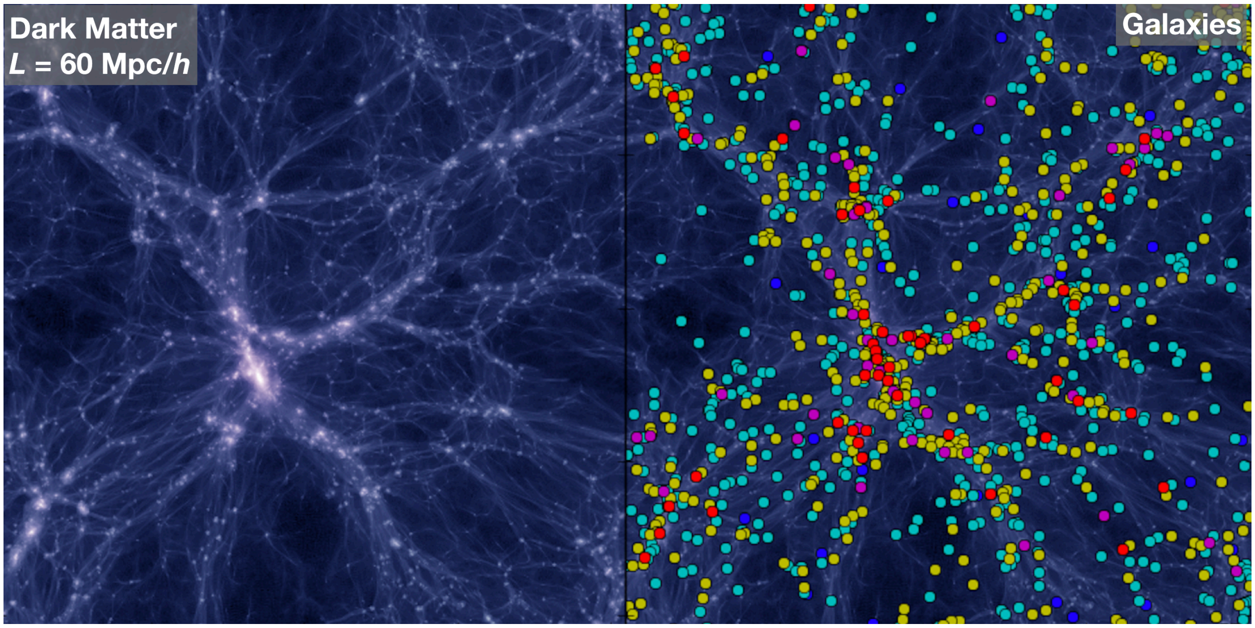

Figure 2: Galaxy formation in cosmic context. Galaxies form within large scale dark matter structures (left) that provide the underlying density distribution for the dissipative formation of their luminous baryonic components. A critical goal of observational galaxy formation is to understand how stellar mass and star formation rate in galaxies are influenced by dark matter structure formation. The right panel shows an example of galaxies color-coded by stellar mass (low-mass:blue, high-mass:red) assigned as a function of halo mass, illustrating how the stellar mass-star formation-halo connection can develop. Space-based IR surveys will unveil the physics behind these relations by simultaneously measuring stellar mass photometrically, star formation rates spectroscopically, and dark matter halo masses through clustering and gravitational lensing.

$z \sim 1-3$ (experience suggests $SNR > 20$ is needed for morphological studies, a limitation for a $m \sim 27$AB survey;[1, 19]). Such a medium-depth survey would return roughly 10x fewer galaxies than the HLS, but the vast majority of the UV luminosity density at $z > 6$ is contributed by galaxies fainter than the HLS limit $m \sim 26.7$AB. An ultra-deep survey that reached $m \sim 29.5$AB over a single WFIRST pointing would provide a similar complement, capturing $\gtrsim 10,000$ faint $z > 6$ galaxies [20]. Indeed, space-based IR survey facilities are likely to employ a "wedding cake" hierarchy of surveys, which may prove effective for studying the connection between galaxy properties and environment at redshifts $z > 1$.

3 Space-Based IR Surveys and Optical Line Emission

High-quality 3D clustering measurements require spectra, and conducting spectroscopic studies in the distant universe in turn requires access to the bright rest-frame optical lines. Our understanding of the rest-frame optical spectroscopic properties of galaxies at $z > 1$ is being transformed by a new generation of near-infrared multi-object spectrographs on the ground, and the HST WFC3/IR grism in space [21, 6, 22]. Future space-based IR surveys will yield a massive sample of 15-20 million Hα redshifts at $z \sim 1.0-1.9$ and 1.5-2 million [OIII] redshifts at $z \sim 1.8-2.8$, over sky regions $\sim 10^5$ times larger than today's best near-infrared spectroscopic surveys. These slitless spectroscopic surveys are optimized for measuring baryon acoustic oscillations but will also map and study the evolution of galaxies in the context of large scale structure. The line-flux limit of WFIRST's HLS survey lies close to the knee of the Hα luminosity function at $z \sim 1.5$, and the space density of galaxies that it will detect corresponds to typical linear scales of 11-12 Mpc. Hα measures a relatively "instantaneous" SFR, and combining clustering and luminosity function measurements will constrain the duty-cycle of star formation. Medium-deep grism surveys with ~ 10 time denser spectroscopic sampling than BAO surveys would enable robust detection of environmental structure and accurate measurements of local densities down to the scale of groups, where most environmental effects on galaxy evolution are expected to play out. Space-based IR surveys will enable archival measurements of galaxy morphologies, stellar population properties, and star-formation rates in the context of environment over a vast dynamic range of scale and density, from pairs and satellites to superclusters and "great walls." Such surveys can therefore bring about a revolution comparable to that of the Sloan Digital Sky Survey (SDSS) for understanding galaxy properties in the context of large-scale structure beyond the relatively local universe.

Slitless spectroscopic IR surveys will also yield spatially-resolved maps of Hα surface brightness, dust extinction, mass-to-light ratio, and metallicity at ~ 1 kpc-scale resolution. Small surveys with the HST/WFC3 IR grism have shown that comparison of such maps to predictions from simulations will provide key constraints to galaxy formation models [23]. Gravitationally-lensed sources will provide emission-line maps at ~ 100s pc resolution [24, 25], allowing us to derive the spatially-resolved emission-line properties of distant galaxies as in nearby systems. Probing how the gradients in interstellar medium metallicity evolve with redshift provides important inputs into models of star-formation feedback [e.g., 26].

4 Finding AGN and Quasars with Space-Based IR Surveys

While star formation can power optical nebular lines, active galactic nuclei powered by supermassive black holes (BHs) also contribute substantially to the cosmic luminosity density in the eras at $z \sim 1 - 2$ probed by IR surveys. BH growth likely provides an essential source of heating in high-mass halos [27], but understanding the role of BH accretion in galaxy formation is hampered by the difficulty in assigning a mass scale to luminous quasars. IR surveys will provide crucial constraints on quasar clustering, complementing its environmental information on galaxy populations for many more moderate luminosity quasars than could be probed by SDSS [28] and over a much wider volume than previous studies [29]. Space-based IR surveys have the potential to reveal the mass of typical accreting BHs at the peak epoch of BH growth at $z \approx 2$ out to $z \approx 7$.

The challenge for space-based IR surveys will be efficiently selecting accreting BHs, and SDSS programs at low-z suggest the most effective way to study active galaxies is emission-line selection within the context of a well-selected galaxy survey [30]. In space-based BAO surveys, one can select active galaxies using strong emission lines [31, 32] and other well-tested emission line / color selection techniques [33]. With an emission-line depth of $\sim 3 \times 10^{-17}\mathrm{erg\ s^{-1}cm^{-2}}$, we expect to reach active galaxies with bolometric luminosities as low as $L_{bol} \sim 10^{43.5}\mathrm{erg\ s^{-1}}$, below the Eddington limit for a typical $\sim 10^8 M_\odot$ BH, and would expect to find thousands of active galaxies in a 10deg^2 survey of 10^4 systems. All accreting BHs vary in time, and with the advent of large-area time- domain surveys the variability selection of active galaxies is growing mature [e.g., 34, 35], and the planned supernova search will provide a useful variability survey. Blue quasars occupy a very distinct locus in color space [36], and space-based IR surveys will efficiently use color selection to find blue quasars out to $z \sim 8$ and probe down the luminosity function beyond LSST or current IR survey limits. Finding these bright quasars will allow us to probe the conditions in the IGM at early times, helping us to understand the affect of quasars on their immediate environments [37], BH growth processes in the early universe [11], and the affect of quasars as a population on the ionization history of the IGM as a whole [38].

Although supermassive BHs are found ubiquitously in the centers of local massive galaxies, we still do not know what physical processes "seed" supermassive black holes at early times [e.g., 39]. Space-based IR surveys will open the exciting prospect to identify low-mass ($\sim 10^6\ M_\odot$) growing BHs at early times (at least as early as $z \approx 8$). For instance, for a ~ 10 deg^2 supernova survey and two three-month observing epochs, each with 3-day sampling and published models for AGN number densities down to ~ 26.5 mag based on the BlueTides simulations [40], there will be tens/deg^2 of AGN powered by $10^6\ M_\odot$ black holes. However, since host galaxies and the AGN will contribute comparable amounts to the bolometric output of the source in the rest-frame UV/optical, cadence information would be used to successfully select AGN candidates based on variability. At these masses, AGN vary on intranight - monthly timescales, so a wide range of cadence should suffice for selection. With a total of 6 or more epochs (even in only two different bands) we expect that with careful image subtraction we will be able to select a sample of roughly 100 potential low-mass seed BHs and learning about the initial conditions for extremely massive SMBHs that form at later times.

5 Space-Based IR Surveys as a Probe of Dark Matter

Space-based IR surveys can test our picture for small-scale dark matter structure formation directly through gravitational lensing. The cold dark matter plus cosmological constant (LCDM) paradigm forms one of the pillars of our models for the origin and evolution of cosmic structures. While remarkably successful at matching observations on large scales, there have been persistent observational challenges to the cold, collisionless dark matter expectations on dwarf-galaxy scales. These "small-scale controversies" may simply stem from a poor understanding of the baryonic processes involved in galaxy formation, or indicate more complex dark sector physics.

Detailed testing of the standard paradigm on small scales remains one of the most pressing issues in galaxy formation. Numerical simulations in LCDM predict a rich spectrum of substructure in galaxy halos. Small fluctuations in the galaxy-scale lensing potential caused by these substructures should result in measurable "flux anomalies" in the magnifications of quadruply-lensed quasar images [41]. While discrepancies between the observed flux ratios and those predicted by a smooth lens model may have been found in radio quasar lenses [42, 43, 44], the small sample size (~ 20 lenses) of current samples limits our understanding. Space-based IR surveys will revolutionize this field by increasing the sample of quad lenses more than 10x [45]. More recently, methods have been developed to use extended lensed sources, in addition to the point-like AGN, to identify substructures through distortions of lensed images. Extended sources are imaged into arcs and rings that probe a larger volume in the lens halo, increasing the number of subhalos that can be sensed. They also can be drawn from larger populations of background sources, typical galaxies rather than bright AGN [e.g., 46], and confirmed by combining with submillimeter observations [47]. The wide-area IR surveys that combine multi-band imaging and spectroscopy, will provide many avenues for identifying large samples of lensed galaxies for such substructure searches and inform us about whether dark matter substructure is as rich as expected.

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