Large Synoptic Survey Telescope Galaxies Science Roadmap

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The *Large Synoptic Survey Telescope Galaxies Science Roadmap* represents the collective efforts of more than one hundred scientists to define the critical research activities to prepare our field to maximize the science return of the LSST dataset. We want to thank the LSST Corporation for their support in developing this Roadmap and for supporting LSST-related science more broadly. We also wish to thank the LSST Galaxies Science Collaboration members for their efforts over the years in developing the case for extragalactic science with LSST. Lastly, we wish to thank Harry Ferguson for his continued efforts to organize this document.

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Abstract

The Large Synoptic Survey Telescope (LSST) will enable revolutionary studies of galaxies, dark matter, and black holes over cosmic time. The LSST Galaxies Science Collaboration (LSST GSC) has identified a host of preparatory research tasks required to leverage fully the LSST dataset for extragalactic science beyond the study of dark energy. This *Galaxies Science Roadmap* provides a brief introduction to critical extragalactic science to be conducted ahead of LSST operations, and a detailed list of preparatory science tasks including the motivation, activities, and deliverables associated with each. The *Galaxies Science Roadmap* will serve as a guiding document for researchers interested in conducting extragalactic science in anticipation of the forthcoming LSST era.

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Chapter 1

Introduction

The Large Synoptic Survey Telescope (LSST) is a wide-field, ground-based observatory designed to image a substantial fraction of the sky in six optical bands every few nights. The observatory will operate for at least a decade, allowing stacked images to detect galaxies to redshifts well beyond unity. LSST and its Deep-Wide-Fast and Deep Drilling Field surveys will meet the requirements of a broad range of science goals in astronomy, astrophysics and cosmology (Ivezic et al., 2008). The LSST ranked first among large ground-based initiatives in the 2010 National Academy of Sciences decadal survey in astronomy and astrophysics (Council, 2010), and will begin survey operations early in the next decade. This document, the *LSST Galaxies Science Roadmap*, outlines critical preparatory research efforts needed to leverage fully the power of LSST for extragalactic science.

In 2008, eleven separate quasi-independent science collaborations were formed to focus on a broad range of topics in astronomy and cosmology that the LSST could address. Members of these collaborations have proven instrumental in helping to develop the science case for LSST (encapsulated in the LSST Science Book; LSST Science Collaboration et al. 2009), refine the concepts for the survey and for the data processing, and educate other scientists and the public about the promise of this unique observatory.

The Dark Energy Science Collaboration (DESC) has taken the next logical step beyond the Science Book. They identified they most critical challenges the community will need to overcome to realize LSSTFLs potential for measuring the nature and effects of dark energy. The DESC looked at five complementary techniques for tackling dark energy, and outlined high-priority tasks for their Science Collaboration during construction. The DESC designated sixteen new and existing working groups to coordinate the work. The DESC documented these efforts in a 133-page white paper (LSST Dark Energy Science Collaboration, 2012). The DESC white paper provides a guide for investigators looking for ways to contribute to the overall DESC preparatory science effort, indicates clearly the importance of the advance work, and connects individual research projects together into a broader enterprise to enable dark energy science with LSST.

Following the lead of DESC, several other LSST community organizations including the AGN, Milky Way and Local Volume, and Solar System Science Collaborations, started to develop Roadmaps to outline critical preparatory tasks in their science domains. This document, led by members of the LSST Galaxies Science Collaboration, acts as a Roadmap for extragalactic science covering galaxy formation and evolution writ large, the influence of dark matter structure formation on the properties of galaxy populations, and the impact of supermassive black holes on their host galaxies. This Roadmap identifies the major high-level science themes of these investigations, outlines how complementary techniques will contribute, and identifies areas where advance work will prove essential. For this preparatory work, the *LSST Galaxies Science Roadmap* emphasizes areas that are not adequately covered in the DESC Roadmap.

Chapter 2 gives a brief summary of the LSST galaxies science background. Many of the themes and projects are already set out in the LSST Science Book, which provides more details for many of the science investigations. Chapter 3 presents preparatory science tasks for extragalactic science with LSST, organized by science topic. The science task list content assumes that the work plan of the DESC will be executed and that the resulting software and other data products resulting from the DESC efforts will be made available to the other science collaborations.

Chapter 2

Galaxy Evolution Studies with LSST

Galaxies represent fundamental astronomical objects outside our own Milky Way. The large luminosities of galaxies enable their detection to extreme distances, providing abundant and far-reaching probes into the depths of the universe. At each epoch in cosmological history, the color and brightness distributions of the galaxy population reveal how stellar populations form with time and as a function of galaxy mass. The progressive mix of disk and spheroidal morphological components of galaxies communicate the relative importance of energy dissipation and collisionless processes for their formation. Correlations between internal galaxy properties and cosmic environments indicate the ways the universe nurtures galaxies as they form. The evolution of the detailed characteristics of galaxies over cosmic time reflects how fundamental astrophysics operates to generate the rich variety of astronomical structures observed today.

Study of the astrophysics of galaxy formation represents a vital science of its own, but the ready observability of galaxies critically enables a host of astronomical experiments in other fields. Galaxies act as the semaphores of the universe, encoding information about the development of large scale structures and the mass-energy budget of the universe in their spatial distribution. The mass distribution and clustering of galaxies reflect essential properties of dark matter, including potential constraints on the velocity and mass of particle candidates. Galaxies famously host supermassive black holes, and observations of active galactic nuclei provide a window into the high-energy astrophysics of black hole accretion processes. The porous interface between the astrophysics of black holes, galaxies, and dark matter structures allows for astronomers to achieve gains in each field using the same datasets.

LSST will provide a digital image of the southern sky in six bands (*ugrizy*). The area ($\sim 18,000$ deg^2) and depth ($r \sim 24.5$ for a single visit, $r \sim 27.5$ coadded) of the survey will enable research of such breadth that LSST may influence essentially all extragalactic science programs that rely primarily on photometric data. For studies of galaxies, LSST will provide both an unequaled catalogue of billions of extragalactic sources and high-quality multiband imaging of individual objects. This section of the *LSST Galaxies Science Roadmap* presents scientific background for studies of these galaxies with LSST to provide a context for considering how the astronomical community can best leverage the catalogue and imaging datasets and for identifying required preparatory science tasks.

LSST will begin science operations during the next decade, more than twenty years after the start of the Sloan Digital Sky Survey (York et al., 2000) and subsequent precursor surveys including PanSTARRS (Kaiser et al., 2010), the Subaru survey with Hyper Suprime-Cam (Miyazaki et al., 2012), and the Dark Energy Survey (Flaugher, 2005). Relative to these prior efforts, extragalactic science breakthroughs generated by LSST will likely benefit from its increased area, source counts and statistical samples, the constraining power of the six-band imaging, and the survey depth and image quality. The following discussion of LSST efforts focusing on the astrophysics of galaxies will highlight how these features of the survey enable new science programs.

2.1 Star Formation and Stellar Populations in Galaxies

Light emitted by stellar populations will provide all the direct measurements made by LSST. This information will be filtered through the six passbands utilized by the survey, providing constraints on the rest-frame ultraviolet SEDs of galaxies to redshift $z \sim 6$ and a probe of rest-frame optical spectral breaks to $z \sim 1.5$. By using stellar population synthesis modeling, these measures of galaxy SEDS will enable estimates of the redshifts, star formation rates, stellar masses, dust content, and population ages for potentially billions of galaxies. In the context of previous extragalactic surveys, LSST will enable new advances in our understanding of stellar populations in galaxies by contributing previously unachievable statistical power and an areal coverage that samples the rarest cosmic environments.

A variety of ground- and space-based observations have constrained the star formation history of the universe over the redshift range that LSST will likely probe (for a recent review, see Madau & Dickinson, 2014). The statistical power of LSST will improve our knowledge of the evolving UV luminosity function, luminosity density, and cosmic star formation rate. The LSST observations can constrain how the astrophysics of gas cooling within dark matter halos, the efficiency of molecular cloud formation and the star formation within them, and regulatory mechanisms like supernova and radiative heating give rise to these statistical features of the galaxy population. While measurement of the evolving UV luminosity function can help quantify the role of these astrophysical processes, the ability of LSST to probe vastly different cosmic environments will also allow for the robust quantification of any changes in the UV luminosity function with environmental density, and an examination of connections between environment and the fueling of star formation.

Optical observations teach us about the established stellar content of galaxies. For stellar populations older than ~ 100 million years, optical observations provide sensitivity to the spectral breaks near a wavelength of $\lambda \approx 4000$Å in the rest-frame related to absorption in the atmospheres of mature stars. Such observations help constrain the amount of stellar mass in galaxies. For passive galaxies that lack vigorous star formation, these optical observations reveal the well-defined "red sequence" of galaxies in the color-magnitude plane that traces the succession of galaxies from recently-merged spheroids to the most massive systems at the centers of galaxy clusters (e.g. Kaviraj et al., 2005). For blue, star-forming galaxies, optical light can help quantify the relative contribution of evolved stars to total galaxy luminosity, and indeed has led to the identification of a well-defined locus of galaxies in the parameter space of star formation rate and stellar mass (e.g., Noeske et al., 2007). This relation, often called the "star-forming main sequence" of galaxies, indicates that galaxies of the same stellar mass typically sustain a similar star-formation rate. Determining the physical or possibly statistical origin of the relation remains an active line of inquiry (e.g. Lofthouse et al., 2017), guided by recently improved data from Hubble Space Telescope over the ~ 0.2 deg^{-2} Cosmic Assembly Near-Infrared Deep Extragalactic Survey (Grogin et al., 2011; Koekemoer et al., 2011). While LSST will be comparably limited in redshift selection, its $\sim 30,000$ times larger area will enable a much fuller sampling of the star formation–stellar mass plane, allowing for a characterization of the distribution of galaxies that lie off the main sequence that can help discriminate between phenomenological explanations of the sequence.

2.2 Galaxies as Cosmic Structures

The structural properties of galaxies arise from an intricate combination of important astrophysical processes. Driven by dark matter structure growth, the dynamical interplay between baryonic and dark matter components form the basis for the development of galaxy properties. The gaseous disks of galaxies require substantial energy dissipation while depositing angular momentum into a rotating structure. These gaseous disks form stars with a surface density that declines exponentially with galactic radius, populating stellar orbits that differentially rotate about the galactic center and somehow organize into spiral features. Many disk galaxies contain (pseduo-)bulges that form through a combination of violent relaxation and orbital dynamics. These disk galaxy features contrast with systems where spheroidal stellar distributions dominate the galactic structure. Massive ellipticals form through galaxy mergers and accretions, and manage to forge a regular sequence of surface density, size, and stellar velocity dispersion from the chaos of strong gravitational encounters. Since these astrophysical processes may operate with great variety as a function of galaxy mass and cosmic environment, LSST will revolutionize studies of evolving galaxy morphologies by providing enormous samples with deep imaging of exquisite quality. These data also enable studies of galaxy mass profiles via weak lensing of the background galaxy population.

The huge sample of galaxies provided by LSST will provide a definitive view of how the sizes and structural parameters of disk and spheroidal systems vary with color, total mass, stellar mass, and luminosity. Morphological studies will employ several complementary techniques for quantifying the structural properties of galaxies. Bayesian methods can yield multi-component parameterized models for all the galaxies in the LSST sample, including the quantified contribution of bulge, disk, and spheroid structures to the observed galaxy surface brightness profiles. The parameterized models will supplement non-parametric measures of the light distribution including the Gini and M20 metrics that quantify the surface brightness uniformity and spatial moment of dominant pixels in a galaxy image (Abraham et al., 2003; Lotz et al., 2004). Given the volume of the LSST dataset, which will also change on short timescales in terms of depth, new machine-learning algorithms (e.g. Hocking et al., 2015, ; Hausen & Robertson, in prep) that enable fast morphological classifications of the LSST survey will be critical in enabling morphological studies from this unique dataset. Collectively, these morphological measures provided by analyzing the LSST imaging data will enable a consummate determination of the relation between structural properties and other features of galaxies over a range of galaxy mass and luminosity previously unattainable.

While the size of the LSST sample supplies the statistical power for definitive morphological studies, the sample size also enables the identification of rare objects. This capability will benefit our efforts for connecting the distribution of galaxy morphologies to their evolutionary origin during the structure formation process, including the formation of disk galaxies. The emergence of ordered disk galaxies remains a hallmark event in cosmic history, with so-called “grand design” spirals like the Milky Way forming dynamically cold, thin disks in the last ~ 10 Gyr. Before thin disks emerged, rotating systems featured “clumpy” mass distributions with density enhancements that may originate from large scale gravitational instability. Whether the ground-based LSST can effectively probe the exact timing and duration of the transition from clumpy to well-ordered disks remains unknown, but LSST can undoubtedly contribute to studying the variation in forming disk structures at the present day. Unusual objects, such as the UV luminous local galaxies identified by Heckman et al. (2005) that display physical features analogous to Lyman break galaxies at higher redshifts, may provide a means to study the formation of disks in the present day under rare conditions only well-probed by the sheer size of the LSST survey.

Similarly, characterizing the extremes of the massive spheroid population can critically inform theoretical models for their formation. For instance, the most massive galaxies at the centers of galaxy clusters contain vast numbers of stars within enormous stellar envelopes. The definitive LSST sample can capture enough of the most massive, rare clusters to quantify the spatial extent of these galaxies at low surface brightnesses, where the bound stellar structures blend with the intracluster light of their hosts. Another research area the LSST data can help address regards the central densities of local ellipticals that have seemingly decreased compared with field ellipticals at higher redshifts. The transformation of these dense, early ellipticals to the spheroids in the present day may involve galaxy mergers and environmental effects, two astrophysical processes that LSST can characterize through unparalleled statistics and environmental probes. By measuring the surface brightness profiles of billions of ellipticals LSST can determine whether any such dense early ellipticals survive to the present day, whatever their rarity.

Beyond the statistical advances enabled by LSST and the wide variation in environments probed by a survey of half the sky, the image quality of LSST will permit studies of galaxy structures in the very low surface brightness regime. This capability will allow for the characterization of stellar halos that surround nearby galaxies. Structures in stellar halos, such as tidal features produced by mergers and interactions and density inhomogeneities, originate from the hierarchical formation process and their morphological properties provides critical clues to the formation history on a galaxy-by-galaxy basis (Bullock & Johnston, 2005; Johnston et al., 2008). Observational studies using small, deep surveys like the SDSS Stripe 82 (e.g. Kaviraj, 2014b,a) and recent work using small telescopes (Martínez-Delgado et al., 2008; Atkinson et al., 2013; Abraham & van Dokkum, 2014; van Dokkum et al., 2014) have demonstrated the critical importance of probing the low surface brightness universe in order to test the hierarchical galaxy formation paradigm. Since low-mass galaxies far outnumber their massive counterparts, the assembly history of massive galaxies is dominated by mergers of unequal mass ratios ('minor' mergers). However, such mergers typically produce tidal features that are fainter than the surface brightness limits of current surveys like the SDSS. Hence, the majority of merging remains, from an empirical point of view, unquantified. Deep-wide surveys like LSST are crucial for empirically testing the hierarchical paradigm and understanding the role of galaxy merging in driving star formation, black hole growth, and morphological transformations over cosmic time (Kaviraj, 2014a). The examination of stellar halos around galaxies will result in the identification of small mass satellites whose sizes, luminosities, and abundances can constrain the nature of dark matter and models of the galaxy formation process at the extreme low-mass end of the mass function.

Finally, observational measures of the outermost regions of thin disks can reveal how such disks "end", how dynamical effects might truncate disks, and whether some disks smoothly transition into stellar halos. LSST will provide such measures and help quantify the relative importance of the physical effects that influence the low surface brightness regions in disks. Other galaxies have low surface brightnesses throughout their stellar structures, and the image quality and sensitivity of LSST will enable the most complete census of low surface brightness galaxies to date. LSST will provide the best available constraints on the extremes of disk surface brightness, which relates to the extremes of star formation in low surface density environments.

The LSST survey uniquely enables precision statistical studies of galaxy mass distribution via weak gravitational. From the radial dependence of the galaxy-mass correlation function, galaxy morphological properties can be compared with the mass distribution, as a function of redshift of the lens galaxy population (Choi et al. 2012, Leauthaud et al. 2012). Even dwarf galaxies can be studied in this way: the LSST survey will enable mass mapping of samples of hundreds of thousands of dwarf galaxies. With a sample of hundreds of millions of foreground galaxies, for the first time trends in galaxy stellar evolution and type can be correlated with halo mass and mass environment on cosmological scales.

2.3 Probing the Extremes of Galaxy Formation

The deep, multiband imaging LSST provides over an enormous area will enable the search for galaxies that form in the rarest environments, under the most unusual conditions, and at very early times. By probing the extremes of galaxy formation, the LSST data will push our theoretical understanding of the structure formation process.

The rarest, most massive early galaxies may form in conjunction with the supermassive black holes that power distant quasars. LSST can use the same types of color-color selections to identify extremely luminosity galaxies out to redshift $z \sim 6$, and monitor whether the stellar mass build-up in these galaxies tracks the accretion history of the most massive supermassive black holes. If stellar mass builds proportionally to black hole mass in quasars, then very rare luminous star forming galaxies at early times may immediately proceed the formation of bright quasars. LSST has all the requisite survey properties (area, multiband imaging, and depth) to investigate this long-standing problem (Robertson et al., 2007).

The creation of LSST Deep Drilling fields will enable a measurement of the very bright end of the high-redshift galaxy luminosity function. Independent determinations of the distribution of galaxy luminosities at $z \sim 6$ show substantial variations at the bright end. The origin of the discrepancies between various groups remains unclear, but the substantial cosmic variance expected for the limited volumes probed and the intrinsic rarity of the bright objects may conspire to introduce large potential differences between the abundance of massive galaxies in different areas of the sky. Reducing this uncertainty requires deep imaging over a wide area, and the LSST Deep Drilling fields satisfy this need by achieving sensitivities beyond the rest of the survey.

The spatial rarity of extreme objects discovered in the wide LSST area may reflect an intrinsically small volumetric density of objects or the short duration of an event that gives rise to the observed properties of the rare objects. Mergers represent a critical class of short-lived epochs in the formation histories of individual galaxies. Current determinations of the evolving numbers of close galaxy pairs or morphological indicators of mergers provide varying estimates for the redshift dependence of the galaxy merger rate (e.g., Darg et al., 2010; Conselice et al., 2003; Kartaltepe et al., 2007; Lotz et al., 2008; Lin et al., 2008; Kaviraj et al., 2009; Robotham et al., 2014; Kaviraj et al., 2015). The identification of merging galaxy pairs as a function of separation, merger mass ratio, and environment in the LSST data will enable a full accounting of how galaxy mergers influence the observed properties of galaxies as a function of cosmic time.

2.4 Photometric Redshifts

As a purely photometric survey, LSST provides an exquisite data set of two-dimensional images of the sky in six passbands. However, the third dimension of cosmic distance to each galaxy must often come from photometric redshifts (photo-z's). Spectroscopic distance estimates rely on the identification of atomic or molecular transitions in expensive, high resolution spectra. In contrast, photometric redshifts estimate the rough distance to an object based on its broad-band photometric colors and, potentially, other properties measurable from imaging. Photo-z measurements are akin to determining redshifts from a very low-resolution but high signal-to-noise spectrum, where each broad-band filter contributes a single sample in that spectrum. Photometric redshifts are therefore sensitive to the large-scale features of a galaxy spectral energy distribution (e. g., the 4000 Å and Lyman breaks), but in general lack the definitiveness of a redshift measured from multiple well-centroided spectral features (e.g., a pair of emission or absorption lines of known separation). As a result, photometric redshifts will generally be more uncertain than spectroscopic redshift estimates and can be affected by degeneracies in the color-redshift relation.

By relying on imaging data alone, we will be able to measure photo-z's for billions of galaxies in the LSST survey. As errors in the assigned redshift propagate directly to physical quantities of interest, understanding the uncertainties and systematic errors in photo-z's is of the utmost importance for LSST and other photometric surveys.Assigning an incorrect redshift to a galaxy also assigns an incorrect luminosity owing to misestimation of both the distance modulus and k-corrections, and hence can bias estimates of the luminosity function. Errors in redshift will also bias the inferred rest-frame colors of a galaxy, propagating to errors in the inferred spectral type, stellar mass, star formation rate, and other quantities. Ideally, estimates of any physical quantity should be performed jointly with a redshift fit, and the expected uncertainties and degeneracies should be fully understood and propagated if measurements are to be made in an unbiased way.

To develop optimal estimates of photo-z's for a particular survey, photo-z algorithms should be trained using a set of galaxies with known redshifts. If spectroscopy is obtained for a fully representative sub-sample of the underlying galaxy population spanning the full domain of application, this spectroscopy can also be used to characterize the biases and uncertainties in the photometric redshift estimates, calibrating their use for science.

Obtaining such a fair spectroscopic sample for LSST will be very difficult to achieve due to limitations in instrumentation, telescope time, and the astrophysical properties of galaxies (e.g., weak spectral features). Biases owing to incomplete training data can be identified and removed using a variety of redshift calibration techniques, such as spatially cross-correlating photo-z-selected datasets with a sample of objects with secure redshifts over wide fields, as will be provided by DESI and 4MOST (Newman, 2008). A detailed plan describing the spectroscopic needs for training and calibrating photometric redshifts for LSST is laid out in Newman et al. (2015), where potential scenarios for obtaining the necessary spectroscopy using existing facilities and those expected to be available in the near future are detailed.

The insights about the formation and evolution of galaxies we expect to gain from LSST can also be used to improve photo-z algorithms, both by constraining the family of spectral energy distributions of galaxies as a function of redshift and by improving our knowledge of distributions of other observable quantities such as size and surface brightness. This mutual synergy between understanding galaxy evolution and improved photometric redshift performance should lead to improvements in both areas as the survey progresses.

2.5 Science Book

The LSST Science Book (LSST Science Collaboration et al. 2009) provided detailed descriptions of foundational science enabled by LSST. The LSST Galaxies Science Collaboration authored the Chapter 9 “Galaxies” of the Science Book, and the table of contents of that chapter follows below to provide an example list of topics in extragalactic science that LSST data will help revolutionize. The interested reader is referred to the LSST Science Book for more details.

1. Measurements, Detection, Photometry, Morphology
2. Demographics of Galaxy Populations
   - Passively evolving galaxies
   - High-redshift star forming galaxies
   - Dwarf galaxies
   - Mergers and interactions
3. Distribution Functions and Scaling Relations
   - Luminosity and size evolution
   - Relations between observables
   - Quantifying the Biases and Uncertainties
4. Galaxies in their Dark-Matter Context
   - Measuring Galaxy Environments with LSST
   - The Galaxy-Halo Connection
   - Clusters and Cluster Galaxy Evolution
   - Probing Galaxy Evolution with Clustering Measurements
   - Measuring Angular Correlations with LSST, Cross-correlations
5. Galaxies at Extremely Low Surface Brightness
   - Spiral Galaxies with LSB Disks
   - Dwarf Galaxies
   - Tidal Tails and Streams
   - Intracluster Light
6. Wide Area, Multiband Searches for High-Redshift Galaxies
7. Deep Drilling Fields
8. Galaxy Mergers and Merger Rates
9. Special Populations of Galaxies
10. Public Involvement

Chapter 3

Task Lists by Science Area

3.1 Active Galactic Nuclei

Active Galactic Nuclei (AGN) phenomena enable an understanding of the growth of supermassive black holes (BHs), aspects of galaxy evolution, the high redshift universe, and other physical activity including accretion physics, jets, and magnetic fields. While AGN represent a distinct topic within the LSST Science Collaborations, the LSST dataset will reveal some aspects of AGN science via their role as an evolutionary stage of galaxies in addition to their ability to probe accretion physics around BHs. The tasks listed here present preparatory science efforts connected with AGN study as a special phase in galaxy evolution.

3.1.1 AGN Selection from LSST Data

AGN-1. *Motivation:* LSST multiband photometry may select Active Galactic Nuclei using a variety of different methods. At optical and near infrared wavelengths, the distinctive colors of AGN at particular redshifts enables their photometric selection. The LSST data will therefore augment methods that rely on X-ray or radio activity, or the identification of emission lines in spectroscopic data. LSST will also open up, in a more practical way, the identification of AGN based on their variability. These LSST photometric, multiwavelength, and variability-selected samples may probe unique aspects of AGN phenomena. A better understanding of the AGN role in galaxy evolution requires an understanding of how and why these selection methods include or exclude particular sources or phases of AGN-galaxy co-evolution.

Activities: The use of LSST as a single way to identify AGN and characterize their diversity of AGN requires the development of selection criteria that can leverage the color, morphology, and variability information available from LSST imaging alone. A number of AGN surveys with input from multiple wavelength observation and spectra already exist, and precursor work must utilize these surveys to determine whether AGN that prove difficult to identify via optical color selection will reveal themselves through the additional parameters of morphology, variability, and/or the near-infrared data that LSST will provide.

Deliverables:

(a) Creation of a cross-matched catalog of known AGN selected and verified using different methods.
(b) Understanding of AGN variability sensitivity given the nominal LSST cadence.
(c) Development of algorithms for color selection account for AGN variability.

3.1.2 AGN Host Galaxy Properties from LSST Data

AGN-2. *Motivation:* Morphological characterizations from parameterized models, such as multiple-component Sersic (1968) profiles, or non-parametric measures like CAS and Gini-M20 (Abraham et al., 1994; Conselice et al., 2000; Lotz et al., 2004) can help identify mergining galaxies in the LSST data. The ability of these techniques to characterize efficiently and accurately the morphology of AGN host galaxies identified via their variability remains unproven.

Activities: Simulated or model AGN host galaxies can characterize whether the LSST Level 2 data will enable the measurement of morphological features associated with AGN, as a function of host galaxy properties, AGN luminosity, and variability. For each model galaxy, varying the central AGN luminosity will reveal the impact of central source brightness on the recovery of morphological properties. Existing data sets, such as Pan-STARRS, may help inform LSST about the range of variability frequency and amplitude, and how these AGN properties may affect the recovery of morphological properties in AGN host galaxies.

Deliverables:

(a) Characterization of the accuracy and precision afforded by the LSST dataset for the recovery of basic morphology properties as a function of AGN brightness and wavelength.
(b) Understanding of the effects of AGN brightness and variability on host-galaxy classification diagrams.
(c) Development of morphological parameters beyond star/galaxy separation and an understanding of the efficacy of LSST Level 2 data products for morphological selection of AGN.
(d) Development of color selection criteria that accounts for morphology.

3.1.3 AGN Feedback in Clusters

AGN-3. *Motivation:* Brightest Cluster/Group Galaxies (hereafter BCGs) represent the most massive galaxies in the local universe, residing at or near the centers of galaxy clusters and groups. BCGs contain the largest known supermassive BHs that can influence the host galaxy properties, cluster gas, and other cluster members via the mechanical energy produced by their $>$ 100kpc scale jets ("AGN feedback"). The relative proximity of low-redshift galaxy clusters enable detailed studies of stars, gas, and AGN jets that may reveal the ramifications of AGN feedback. LSST will provide a large sample of moderate- to high-redshift clusters in which we can measure AGN feedback statistically. By combining X-ray, radio, and optical observations we can assess the average influence of BCG AGN on the hot intracluster medium (ICM) for different sub-populations (e.g., Stott et al., 2012).

Activities: By assembling a multi-wavelength dataset (optical, X-ray, and radio), the BCG mass, cluster mass, ICM temperature, and mechanical power injected into the ICM by supermassive BHs can be constrained. The interplay between the BCG, its black hole, and the cluster gas can then be studied, providing an assessment of the balance of energies involved and a direct comparison with theoretical models of AGN feedback. SDSS has enabled this multi-wavelength analysis for a few hundred clusters at $z < 0.3$, but LSST cluster datasets to reach $z > 1$. Such studies hold implications for cosmological studies by helping to distinguish between X-ray gas properties strongly influenced by AGN in addition to the cluster mass.

Deliverables:

(a) Investigation of the number of BCGs and the mass range of their clusters with redshift that LSST will likely observe.
(b) Compilation of existing and forthcoming radio and X-ray data available for AGN feedback studies (XCS, eROSITA, SKA-pathfinders, SUMSS, etc.).
(c) Assessment of theoretical predictions expected for the multi-wavelength properties of AGN host galaxies in clusters or groups (e.g., cosmological simulations such as EAGLE or more detailed single cluster studies).

3.1.4 AGN Variability Selection in LSST Data

AGN-4. *Motivation:* Most AGN exhibit broad-band aperiodic, stochastic variability across the entire electromagnetic spectrum on timescales ranging from minutes to years. Continuum variability arises in the accretion disk of the AGN, providing a powerful probe of accretion physics. The main LSST Wide-Fast-Deep (WFD) survey will obtain $\sim 10^8$ AGN light curves (i.e., flux as a function of time) with ~ 1000 observations (~ 200 per filter band) over 10 years. The Deep Drilling Fields will provide AGN lightcurves with much denser sampling for a small subset of the objects in the WFD survey. The science content of the lightcurves will critically depend on the exact sampling strategy used to obtain the light curves. For example, the observational uncertainty in determining the color variability of AGN will crucially depend on the interval between observations in individual filter bands. These concerns motivate a determinination of guidelines for an optimal survey strategy (from an AGN variability perspective) and a discovery of possible biases and uncertainties introduced into AGN variability science as a result of the chosen survey strategy.

Activities: Study existing AGN variability datasets (SDSS Stripe 82, OGLE, PanSTARRS, CRTS, PTF + iPTF, Kepler, & K2) to constrain a comprehensive set of AGN variability models. Generate and study simulations using parameters selected from these models using observational constraints, and determine the appropriateness of simulations for carrying out various types of AGN variability science including power spectrum models, quasi-periodic oscillation searches, and binary AGN models.

Deliverables:
(a) Observational constraints on AGN variability models.
(b) Metrics for quantifying the efficacy of different survey strategies for AGN variability science.

3.1.5 AGN Photometric Redshifts from LSST Data

AGN-5. *Motivation:* Given the large number of AGN that LSST will discover, many AGN will not receive follow-up with spectroscopic observations. Photometric redshifts can provide relatively accurate redshifts for large numbers of galaxies, but accurate photometric redshifts for AGN host galaxies remain challenging.

Activities: Initial efforts include a comprehensive review of the state of the art in AGN host galaxy photo-z determinations and an analysis of AGN vs. non-AGN galaxy photo-z performance. A comparison of model and/or observed AGN host SEDs with a matched set of non-host galaxies at a variety of redshifts will help engineer color selection criteria for identifying AGN hosts, and whether variability can break photo-z degeneracies.

Deliverables:

(a) Development of AGN host color selection criteria, and an identification of objects for which color selection might prove ambiguous or degenerate.
(b) Exploration of multiwavelength, morphological, or variability information that might break photo-z degeneracies.

3.1.6 AGN Merger Signatures from LSST Data

AGN-6. *Motivation:* Understanding the role AGN play in galaxy evolution requires identifying AGN phenomena at all stages and in all types of galaxies. AGN host galaxies often show disturbed morphology, suggesting that the galaxy merger process may trigger AGN activity. While the “trainwrecks” may prove easy to identify in the high-quality LSST data, the identification of galaxies in other merger stages, such as “pre-merger” harassment, may be particularly hard to recognize. Preliminary work needs to be done to understand how to identify mergers from the LSST data products and whether galaxy deblending and segmentation methods and procedures are adequate.

Activities: Create simulated or identify real images that contain known galaxy mergers, including systems with and without visible AGN. Run the LSST software stack on these images, and engineer metrics that quantify the accurate detection of galaxy mergers with and without AGN.

Deliverables:
(a) Characterization and optimization of the ability of the LSST Level 2 data to enable the detection of galaxy mergers with AGN.
(b) Identification of merging galaxy properties or categories that will prove challenging to measure using the LSST datasets.

3.2 Clusters and Large Scale Structure

The cosmological process of galaxy formation inextricably links together environment and large scale structure with the detailed properties of galaxy populations. The extent of this connection ranges from the scales of superclusters down to small groups. The following preparatory science tasks focus on this critical connection between galaxy formation, clusters, and large scale structure (LSS).

3.2.1 Cluster and Large Scale Structure Sample Emulator

CLSS-1. *Motivation:* To prepare for galaxy group/cluster and LSS science with LSST, the samples of cluster/group galaxies detected in a given range of redshift, brightness, color, need to be estimated, along with the group and cluster populations identified in given ranges of redshift, richness, mass, and other physical parameters.

Activities: LSST has advanced simulations of its 10-year Wide Fast Deep survey available from the Operations Simulator. The output databases can be analyzed to determine the expected time-dependent depth of LSST detection images at each sky location. These depths can be converted into predicted numbers of galaxies as a function of redshift and brightness (e.g., Awan et al., 2016).

To predict galaxy sample sizes as a function of physical parameters, the "raw" predicted galaxy numbers can be interfaced with semi-analytical models painted on large N-body simulations. This approach can extend the predictions for cluster/LSS samples to include the observed properties of color, size, morphology, and the physical properties of halo mass, stellar mass, and star formation rate. The combination of these models will produce an LSST Cluster/LSS Sample Emulator for understanding the detailed science return of LSST for cluster and group science.

Deliverables:

(a) Creation of a public LSST Extragalactic Sample Emulator with a simple user interface, allowing for the estimation of sample sizes detected by LSST as a function of redshift and physical parameters (e.g. galaxy magnitudes, colors, size, morphology, cluster richness, mass, temperature, etc.).

3.2.2 Identifying and Characterizing Clusters

CLSS-2. *Motivation:* LSST photometry will make it possible to search for and study the galaxy populations of distant clusters and proto-clusters over cosmological volumes. These clusters are testbeds for theories of hierarchical structure formation, intergalactic medium heating, metal enrichment, and galaxy evolution. However, standard approaches for identifying clusters, such as the red sequence method, will be hampered by the limited wavelength coverage of LSST. For example, at $z \gtrsim 1.5$, near-IR photometry is required to identify systems with Balmer/4000Å breaks. To maximize cluster science with LSST, new techniques for cluster identification and the incorporate complementary data from projects such as *Euclid* or *eROSITA* must be devised.

Activities: Using existing imaging datasets and simulations, algorithms need to be developed and optimised to identify clusters at intermediate and high redshift within the LSST footprint. Specifically, this work should characterize the selection function, completeness, and contamination rate for different cluster identification algorithms. Such characerizations require realistic light-cone simulations spanning extremely large volumes, so as to capture significant numbers ($\gg 10,000$) of simulated galaxy clusters at high redshift. Potential algorithms to be tested include adaptations of RedMaPPer (Rykoff et al., 2014) as well as methods that search for galaxy overdensities over a range of scales (e.g., Chiang et al., 2014; Wang et al., 2016). In parallel, a comprehensive search for multiwavelength data (specifically IR and X-ray imaging) is needed to aid in the search for high-z clusters and in the confirmation and characterization of systems at all redshifts.

Deliverables:

(a) Improved cluster identification algorithms that can be applied to LSST data once science operations commence.
(b) Compilation of ancillary data that will be helpful in cluster identification and characterization, such as X-ray (e.g. XCS, eROSITA, etc.), SZ (Planck, SPT, ACT) and radio (SKA and its pathfinders, SUMSS), within the LSST footprint.

3.2.3 Developing and Optimizing Measurements of Galaxy Environment

CLSS-3. *Motivation:* Over the past decade, many studies have shown that “environment” plays a important role in shaping galaxy properties. For example, satellite galaxies in the local Universe exhibit lower star formation rates, more bulge-dominated morphologies, as well as older and more metal-rich stellar populations when compared to isolated (or “field”) systems of equivalent stellar mass (Baldry et al., 2006; Cooper et al., 2010; Pasquali et al., 2010). Unlike spectroscopic surveys, LSST will lack the precise line-of-sight velocity measurements to robustly identify satellite galaxies in lower-mass groups, where the expected photo-z precision will be much coarser than the corresponding the velocity dispersion of typical host halos. Instead, LSST will likely be better suited to measure environment by tracing the local galaxy density and identifying filaments. However, LSST is unlike any previous photometric survey and may require new approaches to measuring environment. The challenge remains to find measures of local galaxy density with the greatest sensitivity to the true underlying density field (or to host halo mass, etc.), so as to enable analyses of environment’s role in galaxy evolution with LSST.

Activities: Using mock galaxy catalogs created via semi-analytic techniques, tracers of local galaxy density (i.e. ”environment”) measured on mock LSST photometric samples will be compared to the underlying real-space density of galaxies or host halo mass. In addition to testing existing density measures, such as N^{th}-nearest-neighbor distance and counts in a fixed aperture, new measures will be explored that may be better suited to LSST. For each measure, the impact of increasing survey depth and photo-z precision over the course of the survey will be examined.

Deliverables:

(a) With an improved understanding of the strengths and weaknesses of different environment measures as applied to LSST, this effort will yield code to measure local galaxy density (likely in multiple ways) within the LSST dataset.
(b) Creation of methods to generate galaxy environmental measures as Level 3 data products for use by the entire project.

3.2.4 Enabling and Optimizing Measurements of Galaxy Clustering

CLSS-4. *Motivation:* Contemporary galaxy surveys have transformed the study of large-scale structure, enabling high precision measurements of clustering statistics. The correlation function provides a fundamental way to characterize the galaxy distribution. The dependence of clustering on galaxy properties and the evolution of clustering provide fundamental constraints on theories of galaxy formation and evolution. Interpreting these measurements provides crucial insight into the relation between galaxies and dark matter halos. Understanding how galaxies relate to the underlying dark matter is essential for optimally utilizing the large-scale distribution of galaxies as a cosmological probe.

Activities: Support work to define and characterize the upcoming galaxy samples from LSST to enable clustering measurements. Several distinct sets of information need to be made available or be calculable from pipeline data. Such requirements include a detailed understanding of any selection effects impacting the observed galaxies, the angular and radial completeness of the samples, and the detailed geometry of the survey (typically provided in terms of random catalogs that cover the full survey area). Further efforts will concern the development, testing, and optimization of algorithms for measuring galaxy clustering using LSST data. One aspect to address is how best to handle the large data sets involved (e.g. the LSST "gold" galaxy sample will include about 4 billion galaxies over 18,000 square degrees). Another issue is the development of a methodology to incorporate optimally the LSST photo-z estimates with the angular data to obtain "2.5-dimensions" for pristine clustering measurements.

These algorithms will be tested on realistic LSST mock catalogs, which will also later serve as a tool for obtaining error estimates on the measurements. This endeavor overlaps with DESC-LSS working group efforts, and requires cooperation of the DESC-PhotoZ working group and the Galaxies Theory and Mock Catalogs working group.

Deliverables:

(a) Guidance for LSST galaxy pipelines to include all the necessary information for measurements of the correlation function and related statistics to take place once LSST data is available.

(b) Development and refinement of techniques for measuring galaxy clustering of large LSST galaxy samples. Together these will enable realizing the full potential of LSST data for large-scale structure studies and galaxy formation inferences thereof.

3.2.5 Disentangling Complicated Lines-of-Sight

CLSS-5. *Motivation:* Lines-of-sight through galaxy clusters and groups rank among the most challenging lines-of-sight along which to measure reliable photometric redshifts as crowding of galaxies complicates the basic process of galaxy photometry, and the presence of significant correlated LSS complicates interpretation of any galaxy redshift distribution computed by algorithms that ignore the presence of LSS. Numerous science goals require the most robust probabilistic statements possible as to the location of galaxies along lines of sight through clusters, for example, identification of background galaxies for weak-lensing, identification of faint cluster members to study the evolution of the luminosity function in clusters, identification of star-forming galaxies in clusters and their infall regions to probe the physics of quenching of star formation.

Activities: LSST will deliver the most information rich dataset ever in relation to the masses and internal

structures of clusters and their infall regions. Moreover, the dataset can be enhanced significantly via the addition of data at other wavelengths, including X-ray, millimeter, and near-infrared.
A tool is therefore envisaged that can take an input catalogue of cluster centers that has been obtained from LSST or any other dataset (e.g. *Planck*, *eROSITA*), extract the basic L2 LSST photometry of objects within a cone centred on the cluster center, and compute the redshift probability distribution $p(z)$ of each galaxy based on a cluster-specific algorithm. When available, t his algorithm will take account of the brightness and extent of X-ray emission, over-density of galaxies as a function of magnitude and color, any available spectroscopic redshifts, and the amplitude and extent of any SZ decrement/increment. The algorithm will likely adopt a Bayesian hierarchical modeling approach to forward model the problem, and can be tested on existing datasets from surveys such as the Local Cluster Substructure Survey (LoCuSS), XXL, and HSC data processed by the DM Stack within LSST.

This work links with efforts on deblending/ICL, forward modeling of cluster and groups, environmental measures, cluster detection, complementary data, and work in the DESC Clusters Working Group via the determination of $p(z)$ for background galaxies.

Deliverables:

(a) A new cluster-specific photometric redshift algorithm that can be applied to a list of cluster detections based on LSST or external data.

3.2.6 Forward Modeling of LSST Clusters and Groups

CLSS-6. *Motivation:* Most of the interesting cluster and group physics from LSST and its union with complementary surveys will be derived from studies that explore the full range of halo mass relevant to groups and clusters $M_{200} \simeq 10^{13} - 10^{15} M_\odot$. This mass range extends beyond that used by cluster cosmologists (e.g. colleagues in DESC), who typically restrict attention to objects with masses $M_{200} > 10^{14} M_\odot$. However, the requirement on controlling systematic biases for cluster/group physics is roughly an order of magnitude less stringent than for dark energy science. Arguably, $\sim 10\%$ control of systematic biases in weak-lensing measurements of low redshift clusters ($\gtrsim 2 \times 10^{14} M_\odot$) has already been achieved (Okabe et al., 2013; Applegate et al., 2014; Hoekstra et al., 2015; Okabe & Smith, 2016). This science task focuses on the challenge of maintaining that level of control down to smaller masses and out to higher redshifts.

Activities: A growing number of studies are adopting an approach of forward modeling the cluster population simultaneously with the cosmological model to obtain constraints on scaling relations and cosmological parameters. Here, the idea is to borrow this same approach, but adopt a fixed cosmological model, broaden the mass range of systems considered, and expand the forward modeling to include additional relationships of interest. For example, one could simultaneously fit density profile models to the shear profiles, the mass-concentration relation, and the star-formation rates of clusters and groups. Overall, this effort will provide a robust Bayesian inference code with which to constrain the physics of galaxies and hot gas in groups and clusters, tied directly to the halo mass function via weak-lensing. Related activities include the selection of elements of the cluster population to include in the model, and the development and testing of the code on simulated data. Once developed, the code can be improved by extending the range of physics explored by adding more physical relations, and by testing the code on existing datasets from pointed surveys (e.g. LoCuSS, others) and wide area surveys (e.g. LoCuSS, DES, others).

Deliverables:

(a) A Bayesian inference code to simultaneously model cluster shear profiles and scaling relations across the full range of halo mass of groups and clusters, to $\sim 10\%$ control on systematics.

3.3 Deep Drilling Fields

The LSST Deep Drilling Fields (DDF) will have a higher cadence and deeper observations than the Wide-Fast-Deep (WFD) survey. Many of the details of the observing strategy have yet to be finalized, but four Deep-Drilling fields have been selected. Whether to include any others will be part of a complex trade involving other special projects that depart from the WFD survey strategy. The details of the observing cadence, final depth in each band, and dithering strategy all remain under study at the current time. The tasks outlined in this section will help optimize the LSST DDF observing strategy, gather supporting data, and ensure that the data processing and measurements meet the needs for galaxy evolution science.

3.3.1 Coordinating Ancillary Observations

DDF-1. *Motivation:* Galaxy evolution science performed using LSST DDF data crucially requires supporting observations from other facilities. While the LSST data uniquely provides deep and accurate photometry, good image quality, and time-series sampling, the amount of information in six bands of relatively broad optical imaging remains quite limited. Estimates of photometric redshifts and stellar-population parameters (e.g., mass and star-formation rate) greatly improve with the addition of longer-wavelength data. Combining these quantities with information on dust and gas from far-IR, millimeter, and radio observations allows one to build and test models that track the flow of gas in and out of galaxies. Deep and dense spectroscopy provides precise redshifts, calibrates photometric redshifts, and measures important physical properties of galaxies. Properly supported by this additional data, the LSST DDFs will become the most valuable areas of the sky for galaxy evolution science. The central regions of the four fields already selected already enjoy multiwavelength coverage; the main challenge is filling out the much larger area subtended by the LSST field of view.

Activities: A major challenge in supporting the LSST DDFs is the huge investment of telescope time. Providing supporting multiwavelength data sets requires coordination across facilities and collaborations to make the most efficient use of telescope time. Current coordination occurs somewhat haphazardly, but there has not to date been a dedicated effort to organize potential stakeholders involved in developing a coherent plan. The LSST Science Collaborations can and should take the lead. The SERVS program to observe the already-designated DDFs with Spitzer provides a good example of where coordination can prove fruitful (Mauduit et al., 2012), but substantial further work remains. Activities include organizing workshops to discuss LSST DDF coordination, and proposals for major surveys or even new instrumentation to provide supporting data. If the proposals are successful, then they must be successfully executed with an eye toward integrating with the future LSST data. These collective efforts will require additional work to enable DDF support through policies and strategic planning at major observatories.

Deliverables:

(a) Workshops on LSST DDF supporting observations.
(b) Annually updated roadmap of supporting observations (conceived, planned, or executed).
(c) Public Release of data from supporting observations.
(d) Level 3 software to enable use of LSST data with supporting data.

3.3.2 Observing Strategy Cadence

DDF-2. *Motivation:* The LSST DDF observing strategy will need to serve diverse needs. For galaxy evolution science, the time series aspect of the observation may prove less important than the depth, image quality, and mix of filters. Non-LSST factors like the availability of supporting data from other facilities, or the timing of the availability of such data will influence the observing strategy optimization. For example, for many science goals completing the observations of one DDF to the final 10-year depth in the first year could prove very beneficial. Justifying this investment will require work, including the selection of a suitable DDF and the identification of synergies with other LSST science areas (e.g., DESC, AGN, transients).

Activities: The LSST observing strategy is optimized using the Operations Simulator (OpSim). The Project works with the community to develop both baseline observing strategies and figures of merit for comparing different strategies. The figures of merit are implemented programmatically via the Metrics Analysis Framework (MAF) so that they can be easily applied to any candidate LSST cadence. The LSST project has called on the Science Collaborations to develop these metrics to codify their science priorities. The major activity here is involvement in the optimization of the DDF strategy through participation in Cadence workshops, training on the MAF and OpSim, developing metrics and coding them in MAF, and proposing and helping to evaluate DDF cadences.

Deliverables:

(a) Figures of Merit via MAF for use by OpSim in evaluating DDF strategies.
(b) Proposed observing strategies for DDFs with corresponding scientific rationale.
(c) Proposing and/or helping to assess selection of additional DDFs.

3.3.3 Data Processing

DDF-3. *Motivation:* Getting the most out of the DDFs may require data processing beyond that required for the LSST WFD Survey. A variety of issues will need consideration in trying to optimize the science output, including different strategies for making co-adds, determining sky levels, treating scattered light, detecting and characterizing faint or low-surface brightness features, deblending overlapping objects, or estimating photometric redshifts. Reprocessing the DDF data while utilizing supporting observations may prove feasible. While there exists a clear advantage to issue one "official" LSST-released catalog at Level 2, defining such a catalog to support a very broad range of science remains challenging. Generating high-quality Level 3 catalogs to advance extragalactic research that include external data will require time and effort from the LSST Science Collaborations.

Activities: Identify the most important DDF-specific science drivers and any processing requirements distinct from the WFD survey. Coordinate with the Project and Science Collaborations to provide a coherent set of specifications and priorities for data processing.

Develop the machinery to test and validate the data-processing on the DDFs (via pure simulations and artificial-source injection). This activity may stress the inputs to the LSST image simulator, requiring more realistic inputs for low-mass galaxies, galaxy morphologies, and low surface brightness features. Use of the supporting data sets in Level 2 or 3 processing requires careful thought. For example, pixel-level information from either Euclid or WFIRST may improve source identification and photometry.

However, these ancillary data sets will not be available for all the DDFs and does not currently reflect the baseline observing plan for any of the projects, and the timing of the various projects and associated data rights create their own set of challenges. The Science Collaborations need to work with the various projects to identify a clear path forward.

Deliverables:

(a) Science drivers and input into to the development of Level 2 processing for the DDFs.
(b) Specifications for galaxy evolution-oriented Level 3 DDF processing.
(c) Specifications for data processing using supporting data from other facilities.
(d) Data simulations tailored to the DDFs.
(e) Level 3 data processing code, or augmentations to the LSST Level 2 pipeline, to fully leverage the depth of the DDFs.

3.4 Galaxy Evolution Task Lists

The LSST Project optimized the observatory and data management design to execute successfully and efficiently the core LSST science mission. For measurements of dark energy, that optimization generally means treating galaxies as "tracer particles" – using statistical measures of ellipticity and position to provide statistical constraints on large-scale structure and cosmic geometry. While many of the DESC tasks relate directly to studying galaxy evolution, they remain incomplete. In particular, studies of galaxy evolution require more attention to optimizing multi-wavelength supporting data, obtaining different kinds of spectroscopy, performing different kinds of simulations and other theoretical support, and a greater attention to the detection and characterization of low-surface brightness features or unusual morphologies.

The task list presented here highlights the preparatory research needed before LSST first light. Tasks of primary importance and particular urgency include those that might influence the detailed survey design or the algorithms used in the LSST Software Stack to construct catalogs. Other critical tasks remain reasonably independent of the LSST survey design and data pipeline optimization, but will help ensure good support for LSST galaxy studies.

3.4.1 Techniques for Finding Low Surface Brightness Features or Galaxies

G-1. *Motivation:* Important scientific benefits of the LSST dataset relative to prior large-area surveys include its ability to detect low-surface-brightness (LSB) features associated with galaxies. This ability includes the identification of tidal streams and other features associated with past and ongoing mergers, intra-cluster and intra-group light, and relatively nearby, extended low-surface-brightness galaxies. Prior to LSST, typical studies of the low-surface-brightness universe focused on relatively small samples, often selected by criteria that prove difficult to quantify or reproduce in theoretical models. Measurements of the LSB features themselves can challenge pipelines and subsequent analysis, and often require both hand-tuning and interactive scientific judgment. This manual attention serves to help quantify accurately what we observe, but such interacting tuning of the measurements does not scale to the LSST dataset and can prove difficult to apply to theoretical models. For LSST, we must automate the detection and characterization of LSB features, at least to the point where we can select samples for further study via database queries and quantify the completeness or other statistical properties of those retrieved samples.

Activities: Several crucial activities include: (1) simulating realistic LSB features, (2) using the simulations to optimize detection and measurement, (3) informing LSST Level 2 processing and observing strategies about the needs of LSB science, and (4) developing a strategy for finding and measuring LSB features through some combination of Level 2 measurements, database queries, and Level 3 processing.

The insertion of realistic LSB features into LSST simulated images will provide "data challenges" to test methods for their extraction and measurement, allowing for the exploration of different techniques or algorithms for performing LSB feature detection and characterization. Because the LSB objects sparsely populate the sky, making realistic LSST sky images will probably prove inefficient. More targeted simulations with a higher density of LSB object will better enable the efficient exploration of LSB feature detection and analysis. Simulated observations must realistically treat scattered light, particularly scattering from bright stars that may or may not fall in the actual field of view of the telescope. Scattering from bright stars will likely contribute the primary source of contamination when searching for extended LSB features. Ideally, the LSST scattered-light model, tuned by repeated observations, will perform sufficiently well and enable the removal or flagging of these contaminants at Level 2. Defining the associated performance metrics for based on analysis of simulation represents an important activity that needs early work to help inform LSST development. Including Galactic cirrus in the simulations is important for very large-scale LSB features. Including a cirrus model as part of the LSST background estimation is worth considering, but the science benefit gained from the additional effort remains unclear.

Because the LSST source extraction is primarily optimized for finding faint, barely-resolved galaxies, simultaneously finding large LSB structures and cataloging them as one entity in the LSST database may pose challenges. For very large structures, analysis of the LSST "sky background" map might constitute the most productive approach. We need to work with the LSST Project to make sure the Software Stack stores the background map in a useful form, and that background measurements from repeated observations can be combined to separate the fluctuating foreground and scattered light from the astrophysically interesting signal owing to extended LSB structures. Then, we need strategies for measuring these background maps, characterizing structures, and developing value-added catalogs to supplement the Level 2 database.

For smaller structures, the database likely will contain pieces of the structure, either as portions of a hierarchical family of deblended objects or as separate catalog entries. Therefore, we need to develop strategies for querying the database to find such structures and either extract the appropriate data for customized processing, or develop ways to put back together the separate entries in the database. A possible value-added catalog, for example, from the Galaxies Science Collaboration might include an extra set of fields for the database to indicate which separate objects likely probably originate from the same physical entity. These additional fields would remain sparsely populated in the first year or two of LSST, but by the end of the survey the relational connections between deblended objects may prove a useful resource for a wide variety of investigations.

Deliverables:

(a) Creations of realistic inputs of LSB galaxies or LSB features for the LSST image simulations.
(b) Development of algorithms for finding and measuring LSB features.
(c) Input to the Project on scattered-light mitigation and modeling strategies.
(d) Input to the Project on photometric and morphological parameters to measure/store at Level 2.
(e) Identification of query strategies and sample queries for finding LSB structures.
(f) Engineering of a baseline concept for a value-added database of LSB structures.

3.4.2 Techniques for Identifying and Deblending Overlapping Galaxies

G-2. *Motivation:* Level 2 data products will provide the starting point for galaxy evolution science with LSST. In the LSST nomenclature, objects represent astrophysical entities (stars, galaxies, quasars, etc.), while sources represent their single-epoch observations. The LSST Software Stack will generate the master list of objects in Level 2 by associating and deblending the list of single-epoch source detections and the lists of sources detected on co-adds. The exact strategies for performing this task still remain under active development by the LSST Project, and engagement with the science community will prove essential. While each data release will provide unique object IDs, if the first few generations of catalogs limit the science performed through data base queries the consequences may impede early LSST science.

For galaxies science, the issue of deblending holds critical importance. For example, searches for high-redshift galaxies via color selection or photometric redshifts involve model or template spectra that make the prior assumption that each analyzed object does not consist of a blend of two objects at two different redshifts. Therefore, to get a reliable estimate of the evolution of classes of galaxies over redshift we need to (a) create reasonably clean initial catalogs and (b) model the effects of blending on the sample selection and derivation of redshift and other parameters. These issues critically affect not just galaxy evolution science, but also lensing and large-scale structure studies. Another example involves the evolution of galaxy morphologies, where the effects of blending and confusion may dominate measurement uncertainties.

For the Level 2 catalogs, the planned approach involves using the Software Stack to deblend sources hierarchically and then maintain this hierarchy in the catalog. Scientifically important decisions still remain about whether and how to use color information in the deblending, and how to divide the flux between overlapping components. Even if the Project performs the development work, engagement with the community can generate important tests and figures of merit to optimize the science return.

Activities: Preparations for LSST in this area involve working both with simulations and real data. The current LSST image simulations already utilize realistic source densities, redshift distributions, sizes, and color distributions. However, the input galaxies do not display realistic morphologies. At least some simulations with realistic morphologies are needed, especially for the Deep Drilling Fields. Inputs should come from hydrodynamical simulations, *Hubble* images, and images from precursor surveys such as CFHTLS, DES and HyperSuprimeCam. The Science Collaborations should help provide and vet inputs.

More challenging activities involve developing techniques and algorithms to improve the deblending. When two galaxies at different redshifts overlap, using observations from all the LSST filters and perhaps even EUCLID and WFIRST might help to disentangle them. Some attempts over the past few years have incorporated color gradient information into the deblending algorithm, but this approach needs much more attention for developing and testing algorithms, and for deciding on figures-of-merit for their performance.

Deliverables:

(a) Production of realistic galaxy image inputs to the LSST ImSim team.
(b) Development of tests and figures of merit to quantify the effects on several science objectives;
(c) Assessment of the current baseline plan for Level 2 deblending and for parameter estimation for blended objects.
(d) Development of prototype implementations of deblending algorithms that take advantage of the LSST color information.

3.4.3 Optimizing Galaxy Morphology Measurements

G-3. *Motivation:* Morphology encodes key signatures of the formation histories of galaxies, and measurements of galaxy morphology provide an important tool for constraining models of galaxy evolution. While simple measures of galaxy ellipticity and position angles may be sufficient for the dark energy science goals, more sophisticated measurements of morphology are needed for galaxy-evolution science. While the "multifit" approach of fitting simple parametric models to galaxy profiles is useful to zeroth order, this approach may be insufficient for the detailed morphological information required for much of the galaxy science that is planned using LSST.

For well-resolved galaxies the baseline requirement is to have separate measures of bulge and disk, spiral arm structure, measures of concentration, asymmetry, and clumpiness. These properties ought to be measured as part of the Level 2 processing, to enable database queries to extract subclasses of galaxies. Both parametric and non-parametric measures are desirable. While Level 3 processing methods will be developed to further optimize galaxy measurements, the Level 2 products should supply enough information to select reasonable subsets of galaxies.

More importantly, while the traditional parameterizations of morphology described above will be useful, it is essential that new, more powerful methods of measuring galaxy morphology are developed and implemented, in order to leverage the exquisite volume and depth of LSST data. In this regard fast, machine-learning techniques (e.g. Hocking et al., 2015, ; Hausen & Robertson, in prep) that can efficiently separate LSST galaxy populations into different morphological classes are particularly relevant and powerful.

Activities: The preparation work will focus on defining morphological parameters and developing machine-learning algorithms to enable users to easily query galaxy morphologies from the LSST database. Two aspects of LSST data make this a significant research project: the fact that LSST provides multi-band data with a high degree of uniformity, and the fact that the individual observations will have varying point-spread functions. The former offers the opportunity to use much more information than has been generally possible. The latter means that it will take some effort to optimize and calibrate the traditional non-parametric measures of morphology (e.g. the CAS, GINI and M20 parameters), develop new LSST-optimized parameters, and tune machine-learning algorithms to operate on this type of data.
Given the very large data set expected from LSST, which will change on short timescales in terms of depth, morphological parameters (e.g. CAS) will likely need to be calibrated on realistic data from hydrodynamical simulations in cosmological volumes, possibly augmented by training sets classified by humans. Similarly, machine-learning algorithms will have to be developed and implemented using a mixture of realistic simulations and precursor datasets, such as the HyperSuprimeCam Survey. A series of “classification challenges” prior to the LSST survey could help to refine these techniques.

Deliverables:

(a) Realistic galaxy image inputs from hydrodynamical simulations and precursor datasets for classification tests.
(b) Human classification of image subsets for calibration of morphological parameters.
(c) Machine-learning algorithms that will provide fast morphological classification of LSST datasets, developed using and implemented on precursor datasets such as the HyperSuprimeCam Survey or the Dark Energy Survey.

3.4.4 Galaxy Structural Parameters

G-4. *Motivation:* The image quality provided by the LSST camera (0.2”/pixel) and the wide field coverage (9.6deg^2) over 18,000 deg^2 in optical and NIR bands promise to provide unique data for studying the evolution of the internal galaxy structure. The full depth of the Wide Fast Deep survey (r $\sim$27.5 coadded) will allow for the identification dwarf galaxies at $z \sim 0.5$, and up to $M_* + 2$ galaxies in clusters and field at $z \sim 1.5$, and reach deep enough to study the structural parameters (size, Sersic index, ellipticity etc.) of M_* galaxies at $z \sim 1.2$ (for seeing< 0.5”). The LSST data will allow for size, Sersic index, and bulge-to-disk ratio for over a billion galaxies to be correlatedd with mass, color, and other intrinsic properties at different epochs and thereby clarify the mechanisms that drive the galaxy assembly and transformation.

Activities: Preparatory work will consist of testing parametric methods for seeing-convolved 2D fitting of the galaxy light distribution on precursor surveys (e.g. Subaru or KiDS) and on simulated LSST images, with the aim of providing viable tools for automatic image masking, catalogue extraction, source classification, and 2D galaxy fitting in Level 3 datasets. This task will involve optimizing tool performance to guarantee meet time metrics (e.g., processing 100 million LSST galaxies in all bands on a single week). The surface brightness profile of galaxies in different bands will finally generate a catalog of all relevant structural parameters via Level 3 products.

Deliverables:
(a) Benchmarks for existing and newly developed tools for galaxy surface photometry.
(b) Automatic masks for star halos, spikes, and reflections, and related procedures for Level 3 analyses.
(c) Tools to catalog structural parameters in different bands.
(d) Machine learning algorithms for the identification of faint substructures in model subtracted images (e.g. streams, merging, rings, strong lensing arcs, etc.).

3.4.5 Optimizing Galaxy Mass Profile Measurements

G-5. *Motivation:* Galaxies form and evolve dynamically via the gravitational influence of the underlying dark matter structure. This non-baryonic dark mass is intimately involved in the evolution of the baryonic component that ultimately generates the stellar component visible in the optical. LSST can uniquely probe both of these tracers for hundreds of millions of galaxies over a range of look-back time. This sample provides an opportunity to probe the detailed relation between baryonic and dark matter structure evolution. Such studies have been attempted before in a limited way using LSST precursor surveys. Using 300,000 lens galaxies in the Deep Lens Survey, (Choi et al., 2012) studied the mass profile of galaxies in three luminosity bins out to several Mpc. Using a similar number of lens galaxies in the COSMOS ACS data,(Leauthaud et al., 2012) derived constraints on the evolution of the stellar-to-dark matter connection in the context of halo models. LSST will provide a billion lens galaxies and more accurate photometric redshifts, revolutionizing this measurement.

Activities: An important issue to address is how far down the galaxy mass function can one detect the mass profile in selected large samples of galaxies. One must start with a model of the mass distribution in galaxies, which will involve use of existing galaxy formation simulations and resulting analytic models. Foreground lens galaxy sample selection must be explored, weak lens shear simulations of LSST observing over a large area (1000 deg^2) containing a large sample of lens galaxies performed, stacked simulations of the galaxy-mass correlation function out to significant radii for mass environment tests (3-10 Mpc) computed, sample cuts on morphological surface brightness type vs. redshift engineered, and an assessment of signal-to-noise (SNR) for dwarf galaxy samples and sample completeness determined. The LSST main survey will have hundreds of thousands of dwarf galaxies in a range of redshift $z = 0.2 - 0.6$ which act as lenses. The shear SNR is high – a simulation of just 20 LSST visits to a single $z = 0.5$ galaxy with total $10^{11} M_\odot$ virial mass yields a shear SNR$\approx$ 10 out to several Mpc in projected radius. Stacking a million dwarf galaxies should thus yield high precision mass profiles, even when cut on parameters such as mass environment, surface brightness type, stellar mass, and redshift.

Deliverables:

(a) A selection for a set of template galaxies for use as lenses in ray-trace simulation, using a set of simulated models of galaxies at various stages in development.
(b) Galaxy - mass shear simulations over at least 1000 square degrees, using the latest LSST OpSim run and full end-to-end weak lens ray tracing, including PSF and detector effects, and incorporating a representative set of galaxies over a range of masses.
(c) Computation of galaxy-mass correlation functions using these stacked LSST shear simulations, for sets of populations of galaxies over a wide mass range.
(d) Assessment SNR vs galaxy mass, and the ability to correlate mass profile with optical surface brightness and type over a range of redshift.

3.4.6 Optimizing Galaxy Photometry

G-6. *Motivation:* Systematic uncertainties will dominate over random uncertainties for many research questions addressed with LSST. The most basic measurement of a galaxy is its flux in each band, but flux is a remarkably subtle measurement for a variety of reasons as galaxies do not have well-defined edges, their shapes vary, they have close neighbors, they cluster together, and lensing affects both their brightness and clustering. These factors all affect photometry in systematic ways, potentially creating spurious correlations that can obscure or masquerade as astrophysical effects. For example, efforts to measure the effect of neighbors on galaxy star-formation rates can be erroneous if the presence of a neighbor affects the basic photometry. Measurements of galaxy magnification or measurements of intergalactic dust can be similarly affected by systematic photometric biases. It is thus important to hone the photometry techniques prior to the survey to minimize and characterize the biases. Furthermore, there are science topics that require not just photometry for the entire galaxy, but well-characterized photometry for sub-components, such as a central point-source or a central bulge.

Activities: The core photometry algorithms will end up being applied in Level 2 processing, so it is important that photometry be vetted for a large number of potential science projects before finalizing the software. Issues include the following. (1) Background estimation, which, for example, can greatly affect the photometry for galaxies in clusters or dwarfs around giant galaxies. (2) Quantifying the biases of different flux estimators vs. (for example) distances to and fluxes of their neighbors. (3) Defining optimal strategies to deal with the varying image quality. (4) Defining a strategy for forced photometry of a central point source. For time-varying point-sources, the image subtractions will give a precise center, but will only measure the AC component of the flux. Additional measurements will be needed to give the static component. (5) Making use of high-resolution priors from either Euclid or WFIRST, when available. Because photometry is so central to much of LSST science, there will need to be close collaboration between the LSST Project and the community.

Deliverables:

(a) Development of metrics for various science cases to help evaluate the Level 2 photometry.
(b) Realistic inputs for difficult photometry cases (e.g. close neighbors, clusters of galaxies, AGN in galaxies of various morphologies).

Deliverables over the longer term include developing optimal techniques for forced photometry using priors from space-based missions.

3.4.7 Optimizing Measurements of Stellar Population Parameters

G-7. *Motivation:* The colors of galaxies carry information about their star formation histories, each interval of redshift being a snapshot of star formation up until that time. Unfortunately, estimates of star formation rates and histories for a single galaxy based on only the LSST bands will be highly uncertain, owing largely to degeneracies between age, dust extinction, and metallicity. Strategies for overcoming the degeneracies include hierarchical modeling – using ensembles of galaxies to constrain the hyper-parameters that govern the star formation histories of sets of galaxies rather than individuals, and using ancillary data from other wavelengths.

Activities: Activities in this area include developing scalable techniques for hierarchical Bayesian inference on very large data sets. These can be tested on semi-analytical or hydrodynamical models, where the answer is known even if they do not correctly represent galaxy evolution. The models should also be analyzed to find simple analytical expressions for star formation histories, chemical evolution, and the evolution and behavior of dust to make the Bayesian inference practical.

Deliverables:

(a) Development and refinement of techniques for constraining star-formation histories of large ensembles of galaxies.
(b) Model inputs to guide in developing these techniques.
(c) Refinement of the science requirements for ancillary multi-wavelength data to support LSST.

3.5 High-Redshift Galaxies

Observations of distant galaxies provide critical information about the efficiency of the galaxy formation process, the end of the reionization era, the early enrichment of the intergalactic medium, and the initial conditions for the formation of modern galaxies at later times. Through its wide area and sensitivity in zy, LSST will probe galaxies out to $z \sim 7$ and yet further in conjunction with future wide-area infrared surveys. The following science tasks address outstanding preparatory work for maximizing high-redshift science with LSST.

3.5.1 Optimizing Galaxy Photometry for High-Redshift Sources

HZ-1. *Motivation:* The identification and study of high-redshift galaxies with LSST hinges on reliable, accurate and optimal measurements of the galaxy flux in all LSST passbands. Galaxies at redshifts above $z \sim 7$ will only be detected in the LSST y-band and will be non-detections or "drop-outs" in the other LSST filters. Galaxies at redshifts $z > 8$ will not be detected at all in the LSST filters, but combining LSST with infrared surveys such as Euclid and WFIRST would enable the identification of this population. Robust flux measurements or limits for the undetected high-redshift galaxies in the blue LSST filters will prove particularly important, as this information enables efficient high-redshift galaxy selection. The highest redshift searches will LSST will necessarily require combining with space-based infrared surveys like Euclid and WFIRST. Since Euclid and WFIRST will provide data with very different spatial resolutions and point spread functions (PSFs) compared to LSST, algorithms also need to be devised to provide homogeneous flux measurements for sources across the different surveys. It remains unclear whether the current LSST Level 2 data will meet all the requirements for identifying and characterizing high-redshift galaxy populations, motivating an investigation before the start of LSST operations.

Activities: First, the potential need for Level 3 data products beyond the baseline LSST Level 2 catalog requires clarification. Photometric catalogues produced using the reddest LSST (e.g. z- or y-band) images as the detection image will prove critical for high-redshift science as high-redshift galaxies will not be detected in the bluer bands. Similarly, negative fluxes for undetected galaxies together with their corresponding errorbars provide useful input into spectral energy distribution (SED) fitting codes for high-redshift galaxy selection. Coordinating with the LSST Project to ensure the application of forced photometry in Level 2 in a manner appropriate for high-redshift galaxy selection may be sufficient, or Level 3 data products may be required.

Second, the determination of a suitable approach to combining LSST data with infrared data from Euclid/WFIRST for high-redshift galaxy selection will be required, including optimal measures of an optical-IR color for sources from these combined datasets. Sources resolved in Euclid or WFIRST data could be blended in LSST, and may therefore require deblending using the higher resolution IR data as a prior before reliable flux and color measurements can be made. The engineering of this combined analysis likely will require Level 3 efforts, and tests using existing datasets (e.g., Dark Energy Survey and Hubble Space Telescope data) may already commence.

Deliverables:

(a) Clarification of LSST Level 2 data suitability for high-redshift science, and an identification of any Level 3 needs.
(b) Development of Level 3 tools to produce optimal combined photometry from ground and space-based surveys, and the testing of these tools on existing datasets.

3.5.2 High-Redshift Galaxies and Interlopers in LSST Simulations

HZ-2. *Motivation:* Before the start of LSST operations, the testing of selection methods for high-redshift galaxies on high-fidelity simulations will provide essential validation of the utility of LSST data for studying distant galaxy populations. Given its wide-field coverage, LSST will uniquely uncover large samples of the most luminous and potentially massive high-redshift galaxies at the Epoch of Reionization (Robertson et al., 2007). The most significant obstacle to selecting clean samples of such sources from the photometric data is the presence of significant populations of interlopers, such as cool brown dwarfs in our own Milky Way and low-redshift, dusty and/or red galaxies. These objects can mimic the colors of high-redshift sources and therefore prove difficult to distinguish. This issue is particularly a problem for the highest redshift objects detected by LSST, which, unless data at redder wavelengths is available (such as near-infrared imaging from VISTA/Euclid/WFIRST, and/or mid-infrared imaging from Spitzer/WISE) will be only detected in one or two red-optical filters. Using the LSST simulations, one wants to devise the most effective way of separating these different populations by utilizing both photometric and morphological information for the sources. Based on experience with ground-based surveys such as the Dark Energy Survey and VISTA, one expects LSST images to spatially resolve at least some of the most luminous $z > 6$ galaxies (Willott et al., 2013; Bowler et al., 2017). For fainter high-redshift galaxies however, a morphological distinction between faint ultra-cool brown dwarfs may not be possible, and further information such as near-infrared colours or proper motions will be required for identification.

Activities: Liaise with the LSST Project simulations working group to ensure that high-redshift galaxies have been incorporated into the simulations with a representative set of physical properties (e.g., star formation histories, UV-slopes, emission line equivalent widths, dust extinction, and metallicity). Ensure that high-redshift galaxies have the correct number density and size distribution in the simulations, allowing for investigations to characterize how effectively morphology can separate high-redshift galaxies from low-redshift interlopers. The high-redshift quasar population should also be included, as these have comparable number densities to the brightest galaxies at these redshifts and are typically indistinguishable with broad-band photometry only. Incorporate interloper populations into the simulations with the correct number densities and colors, including cool Milky Way stars (e.g., M, L and T-brown dwarfs) as well as populations of very red, massive, and/or dusty galaxies at lower redshifts of $z \sim 2$. Determine the degree to which LSST selection of high-redshift galaxies effectively requires color information from infrared filters provided by external surveys (i.e., Euclid or WFIRST).

Deliverables:

(a) Incorporation of high-z galaxies and quasars into LSST simulations with a realistic and representative set of properties.
(b) Incorporation pf cool Milky Way brown dwarfs into LSST simulations.
(c) Predictions of the likely number density of brown dwarfs over the different DDFs.
(d) Extension of simulations to other datasets beyond LSST (e.g., Euclid and WFIRST filters).

3.6 Low Surface Brightness Science

The exquisite data quality of LSST will open up a brand new regime in low surface brightness (LSB) science, over unprecedentedly large areas of the sky. LSST's unique deep-wide capabilities will enable us to uncover new evidence for and measures of the cosmic merger rate (via tidal features that result from galaxy interactions), reveal the signatures of hierarchical structure formation in extragalactic stellar halos, and probe the LSB outskirts around local galaxies. The following science tasks provide an enumeration of the critical preparatory research tasks required for fully leveraging the LSST dataset for LSB science.

3.6.1 Low Surface Brightness Tidal Features

LSB-1. *Motivation:* A key advantage of LSST over previous large area surveys (e.g. the SDSS) is its ability to detect LSB tidal features around galaxies, which encode their assembly history (e.g. Kaviraj, 2014a). The LSST survey (which has a larger footprint than the SDSS) will be two magnitudes deeper than the SDSS almost immediately after start of operations, and five magnitudes deeper at the end of the survey. With this unparalleled deep-wide capability, LSST will revolutionize LSB tidal feature science, enabling, for the first time, the empirically reconstruction of the assembly histories of galaxies over at least two-thirds of cosmic time. These histories provide the most stringent observational test yet of the hierarchical paradigm and elucidate the role of mergers (down to mass ratios of at least 1:50) in driving star formation, black-hole growth, and morphological transformation over a significant fraction of cosmic time.

Prior to LSST, typical studies of the LSB universe have focused on small galaxy samples (e.g. in the SDSS Stripe 82), often selected using criteria that are difficult to quantify (e.g. visual inspection, that can be somewhat subjective) or reproduce in theoretical models. Furthermore, previously used techniques for the identification and characterization of features, such as visual inspection, cannot be easily applied to the unprecedented volume of data expected from the next generation of telescopes like LSST. Given the depth and volume of data expected from LSST, it is critical that we automate the detection, measurement and characterization of LSB tidal features, at least to the point where samples for further study can be selected via database queries, and where the completeness of samples returned from such queries can be quantified.

Activities: Several activities are of critical importance and need to be completed before LSST commissioning and the survey proper:

(a) Simulating realistic LSST images and LSB features (using e.g. new high-resolution hydrodynamical simulations in cosmological volumes, such as Horizon-AGN, EAGLE, Illustris and others).

(b) Identifying precursor datasets (e.g. the HyperSuprimeCam Survey or the Dark Energy Camera Legacy Survey (DECaLS)) that can be used as testbeds for developing LSB tools for use on LSST data.

(c) Using such simulations to develop algorithms for auto-detection, measurement and characterisation of LSB features (e.g. using the properties of LSB tidal features to back-engineer the properties of the mergers which created them).

(d) Applying these algorithms to the precursor datasets to test their suitability.

(e) Ensuring that LSST level-2 processing strategies and observing strategies are aligned with the needs of LSB tidal-feature science.

Deliverables:

(a) Realistic mock LSST images from cosmological simulations (including re-simulations of individual objects where necessary) with spatial resolutions of ~ 1 kpc or better.

(b) Algorithms for finding galaxies with LSB tidal features, measuring the properties of these features and characterizing them i.e. using the properties of LSB tidal features to reconstruct the properties of the mergers which created them (e.g. mass ratios, time elapsed since the merger, etc.).

(c) A baseline concept for a value-added LSST database of LSB tidal features.

3.6.2 Low Surface Brightness Galaxies

LSB-2. *Motivation:* The objective of this task is to investigate objects that have surface brightnesses much less than the background night sky and are typical of the Milky Way galaxy within which we live. Many authors have previously shown how difficult it is to identify LSB galaxies and, more importantly, that our current observations may be severely biased towards detecting objects that have surface brightnesses very similar to our own spiral galaxy. Thus, the universe we perceive may have more to do with the position we are observing it from than its true nature - what would we see if we were able to move our telescopes away from the Sun and out to the very outer edges of the Galaxy?

Additionally, the LSB universe includes a large percentage of galaxies representing the low-mass end of the galaxy mass function, which in turn has been a major source of tension for the LCDM cosmological model (Kaviraj et al., 2017). The galaxy mass function at masses less than $M_h \sim 10^{10}$ $M_\odot$ systematically departs from the halo mass function in ways that are difficult to reconcile with current models of baryonic feedback. On the observational side, a crucial step towards understanding the discrepancy is to derive a much more complete census of low-mass galaxies in the local universe. For gas-poor galaxies, which includes most dwarfs within the halos of Milky-Way like galaxies, detection via neutral hydrogen surveys or emission-line surveys is nearly impossible. Dwarf galaxies in the Local Group can be found by searching for overdensities of individual stars. At much larger distances, this becomes impossible. However, these galaxies will still be quite easy to detect in LSST images.

At the other extreme of LSB galaxies, the largest spiral galaxy known since 1987 (called Malin 1), has an extremely LSB disk of stars and an impressive system of spiral arms. The central bulge of the galaxy is prominent, but the stellar disk and spiral arms only revealed itself after sophisticated image processing. Malin 1 was discovered by accident and has for almost thirty years been unique. How many more galaxies with rather prominent central bulges also have extended LSB disks? This issue is very important for understanding the angular momentum distribution of galaxies and where this angular momentum comes from - for its stellar mass Malin 1 has about a factor ten higher angular momentum than typical values. The limiting surface brightness limit of the LSST combined with the large field-of-view make this facility unique for probing the existence of large LSBs similar to Malin 1. There is also an existing problem relating galaxies formed in numerical simulations to those observed. Models with gas, cooling and star formation lose gas and angular momentum making disc galaxies too small. This has already been termed the angular momentum catastrophe and galaxies with giant disks like Malin 1 only make this problem worse. This issue is particularly important as there is increasing evidence that angular momentum plays a large part in determining the morphology of galaxies, a problem that has plagued galaxy formation studies since its inception.

To quantify the astronomical problem we can give some approximate numbers. The typical sky background at a good dark astronomical site is ≈ 22.5 mag arcsec^{-2} and that from a space telescope typically an order of magnitude fainter ≈ 25.0 mag arcsec^{-2}. The mean surface brightness (averaged over the half-light radius) of a galaxy like the Milky Way is ≈ 23.0 mag arcsec^{-2}, of order the brightness of the darkest sky background seen from the ground. The mean surface brightness of the giant LSB galaxy Malin 1 is about ≈ 28 mag arcsec^{-2}, some 100 times fainter than that of the Milky Way and that of the sky background. Extreme dwarf galaxies in the Local Group have mean surface brightnesses as faint as ≈ 32 mag arcsec^{-2}, 10^4 times fainter than the background, but these have only been found because they are resolvable into luminous stars - something that is not currently possible to do from the ground for distances beyond about 5 Mpc. Note that 26 mag arcsec^{-2} corresponds to approximately a surface density of about one solar luminosity per sq parsec. Our intention is to explore the universe using LSST to at least a surface brightness level of 30 mag arcsec^{-2}.

Activities: The key activities for this task include the production of simulated data e.g. from new hydrodynamical simulations in cosmological volumes (such as Horizon-AGN, EAGLE, Illustris etc.) that can be passed through the LSST data reduction pipeline. Once produce, analysis of simulated images is needed to ensure that LSB galaxies can be accurately detected. This analysis will require the development of new object detection software specifically designed for the detection of LSB galaxies, in particular objects with large size, near or melted with brighter galaxies, and highly irregular and distorted objects. Precursor data sets that can be used to test our methods will need to be identified. Data generated using numerical simulations can be used to examine the types of galaxies produced that have sufficient angular momentum to become LSB disks. These disks can be quantified and placed within simulated data to test the ability of the pipeline to preserve LSB features. New methods of detecting LSB objects will be engineered, including pixel clustering methods and the labeling of pixels with certain properties, i.e., surface brightness level, SED shape, and proximity to other similar pixels. We will train our methods on other currently available data sets (KIDS, CFHT etc). These analyses will further require the production of realistic simulated LSST images of nearby dwarf galaxies (from high resolution hydrodynamical simulations like New Horizon which has resolutions of tens of parsecs), the identification of nearby semi-resolved dwarf galaxies in precursor data sets to use to develop the LSST tools, and the development and testing of the database search queries for finding candidates of several shapes and sizes.

Deliverables:

(a) Realistic mock LSST images of LSB galaxies from simulations.
(b) Detection and selection algorithms for LSB galaxies from observational datasets.
(c) A new Level 3 LSB galaxy detection package.

3.6.3 Faint Outskirts of Galaxies

LSB-3. *Motivation:* The outskirts of nearby galaxies, loosely defined as the regions below $25-26$ mag arcsec^{-2} in surface brightness, have long been studied mainly in neutral hydrogen, and later in the UV thanks to the exquisite imaging by GALEX. Deep optical imaging of these regions has been performed on individual objects or on small samples by using extremely long exposures on small (including amateur and dedicated) telescopes, using the SDSS Stripe82 area, and using deep exposures with large telescopes (e.g., CFHT, Subaru, GTC). The main science driver for studying the outskirts of galaxies is understanding the assembly, formation, and evolution of galaxies. These studies can be performed through imaging and subsequent parameterization of structural components such as outer exponential disks, thick disks, tidal streams, and stellar halos. From numerical modeling, it is known that the parameters of these components can give detailed information on the early history of the galaxies. For instance, halo properties, and structure within the stellar halo are tightly related to the accretion and merging history, as illustrated by the imaging of structures in the stars in the outskirts of M31 and other local group galaxies.

Ultra-deep imaging over large areas of the sky, as will be provided by LSST, can in principle be used to extend the study so far mostly limited to Local Group galaxies to 1000s of nearby galaxies, and even, at lower physical scales, to galaxies at higher redshifts. It is imperative, however, to understand and correct for a number of systematic effects, including but not limited to internal reflections and scattered light inside the telescope/instrument, overall PSF, including light scattered by the brighter parts of the galaxy under consideration, flat fielding, masking, residual background subtraction, and foreground material (in particular Galactic cirrus). Many of these effects, and in particular the atmosphere part of the PSF vary with position and/or time on timescales as short as minutes, need to be understood before stacking. The systematics will affect some measurements more than others – for instance, linear features such as tidal streams will be less affected by overall PSF.

Activities: Most of the activities to be performed in relation to this task will be in common with other LSB tasks, in particular those related to understanding the systematics and how they vary with time and position on the sky. Good and very deep PSF models will have to be built, likely from a combination of theoretical modelling and empirical measurements, and the PSF scattering of light from the brighter parts of the galaxies will need to be de-contaminated and subtracted before we can analyse the outskirts. Dithering and rotation of individual imaging will need to be modelled before stacking multiple imaging. Commissioning data will need to be used to study the temporal and positional variations of the PSF, and how accurate theoretical predictions for the PSF are (in other words, how much a variable atmospheric PSF component complicates matters).

Deliverables:

(a) Information on the stability and spatial constancy of the LSST PSF.
(b) Improved control over systematics for LSB science, and other fields including weak lensing.

3.6.4 Intracluster Light

LSB-4. *Motivation:* Intra-cluster Light (ICL) is a low surface brightness stellar component that permeates galaxy clusters. ICL is predicted to be formed mainly of stars stripped from cluster galaxies via interactions with other members, which then become bound to the total cluster potential. The ICL is also likely to contain stars that formed in the gaseous knots torn from in-falling galaxies as they are ram-pressure stripped by the hot intra-cluster medium. Therefore, it is important to study the ICL as it has kept a record of the assembly history of the cluster. Assuming LSST and its data products are sensitive to large LSB structures (see Activities and Deliverables) then it will be possible to perform the first comprehensive survey of ICL in galaxy clusters and groups within a uniform dataset.

Some outstanding scientific questions, which LSST could solve are as follows:

- When does the ICL (to a given SB limit) first emerge i.e. at what redshift and/or halo mass?
- Does the ICL contain significant substructure?
- What is its surface brightness profile and does it have a color dependence, which would indicate

age/metallicity gradients?

- Where does the ICL begin and the large diffuse cD halo of the Brightest Cluster Galaxy (BCG) end and do they have the same origin?

Activities: The preparatory work for the ICL component of the LSB case involves investigating LSST-specific issues for large LSB features and the known properties of the ICL itself. The LSST specific issues fall into three categories: telescope; observation strategy; and pipeline. The faint, large radii wings of the PSF and any low-level scattered light or reflections from the telescope optics or structure will produce LSB signals, which could easily mimic the ICL. The dither pattern of the observations, if smaller than the typical extent of a cluster, could mean that the ICL is treated as a variation in the background during the reduction and/or image combination process, rather than as a real object. This leads onto the pipeline itself which, regardless of the dither pattern, could remove the ICL if an aggressive background subtraction is used on either single frames or when combining images. It is therefore crucial to liaise with the LSST Project's strategy, telescope, instrument and data reduction teams.

The ICL specific issues are mainly the feasibility of observing the ICL given its known properties, which can be simulated from existing data. Using deep observations of the ICL in low redshift clusters one can model whether it is expected to see ICL at higher redshifts (up to $z = 1$) given dimming, stellar population evolution, and the surface brightness limits of LSST. This consideration is crucial for determining possible evolution in ICL properties. For studies of low mass groups or high redshift systems, it may be required to stack populations to obtain a detection of the ICL. An assessment of whether a genuine stacked ICL detection could be achieved by a comprehensive masking of galaxy cluster members is important, as is a determination of whether faint galaxies just below the detection threshold end up combining to give a false or boosted ICL signal.

Deliverables:

(a) An investigation of telescope specific issues that affect the measurement of large LSB features: PSF wings; scattered light.

(b) An investigation of observation specific issues that affect the measurement of large LSB features: dither pattern strategy.

(c) An investigation of image pipeline specific issues that affect the measurement of large LSB features: background removal; image combining.

(d) A feasibility analysis: given the depth/surface brightness limit of the LSST imaging, to what limits can we hope to recover ICL in clusters and to what redshifts? Can this be simulated or extrapolated from deep imaging of low-z clusters?

(e) An investigation of the feasibility of stacking clusters to obtain faint ICL - this is difficult and will require very strong masking of even the faintest observable cluster members.

3.7 Photometric Redshifts

For a photometric survey like LSST, our abilities to accurately measure distances to huge samples of galaxies, constrain the stellar masses, ages, and metallicities of objects as a function of time, measure the spatial clustering of galaxy populations, and identify unusual objects at various cosmic epochs will all rely heavily on photometric redshift measurements. The following important preparatory science tasks address both the systematic uncertainties on photometric redshifts associated with the LSST observatory and with the requisite stellar population synthesis models.

A major effort within the LSST Dark Energy Science Collaboration (DESC) is focused on the development of photometric redshift algorithms for LSST, including the incorporation of joint probability distributions between redshift and astrophysical parameters of interest for the study of galaxy evolution. Efforts within the Galaxies collaboration should be able to leverage work happening in DESC and build upon it to ensure that photometric redshifts optimized for galaxy science are available.

3.7.1 Impact of Filter Variations on Galaxy Photometric Redshift Precision

PZ-1. *Motivation:* For accurate photometric redshifts, well-calibrated photometry is essential. Variations in the telescope system, particularly the broad-band *ugrizy* filters, will need to be very well understood to meet the stringent LSST calibration goals. Photometry will be impacted by multiple factors that may vary as a function of position and/or time. The position of the galaxy in the focal plane will change the effective throughput both due to the angle of the light passing through the filter, and potential variations in the filter transmission itself due to coating irregularities across the physical filter. Preliminary tests show that the filter variation may have a relatively small impact, but further tests are necessary to ensure that these variations will not dominate the photometric error budget.

In addition, the effective passbands of the LSST filters will depend significantly upon atmospheric conditions and airmass, particularly in y-band. The spatially correlated nature of these effects can induce scale-dependent systematics that could be particularly insidious for measurements of large-scale environment and clustering. The nominal plan from LSST Data Management is to correct for variations across the focal plane or between, incorporating approximate models for galaxy SEDs (which may be based upon photometric redshift estimates). Such corrections may be imperfect and leave residuals, particularly for specific populations with unusual SEDs.

Tests of the amplitude of these residuals and their impact on photo-z's, especially for particular object classes of interest, will be important for determining to what degree DM data products can be used directly for galaxies work. If the variations can be calibrated well, they could potentially be used to further improve, rather than degrade, photo-z performance. The variations in filter response can offer up a small amount of extra information on the object SED given the slight variation in effective filter wavelength, particularly for objects with strong narrow features (i.e., emission lines). Tests of how much information is gained can inform whether or not the extra computational effort required for computing photo-z's that incorporate the effective passband from every individual LSST observation of an object will be superior to estimates incorporating DM measurements corrected to the six fiducial filters of the survey. All topics discussed above are also being examined by the LSST Dark Energy Science Collaboration Photometric Calibration working group, and there are several related tasks described in the DESC Science Roadmap document[1]. Communication and coordination with the Photometric

[1] The DESC Science Roadmap is available at: http://lsst-desc.org/sites/default/files/DESC_SRM_V1_0.pdf

Calibration group will be very important to maximize the impact of work on these areas of shared interest.

Activities: Tests of the SED-dependent residuals in photometric redshifts induced by photometric calibration systematics at the expected level.

Deliverables:
(a) Quantification of the amplitude of photometric uncertainties in the LSST filters due to variation in filter throughputs and atmospheric transmission.
(b) Identification of SED classes where residuals in DM calibration of effective passbands will be prominent.

3.7.2 Photometric Redshifts in the LSST Deep Drilling Fields

PZ-2. *Motivation:* The LSST Deep Drilling Fields present different challenges than the main survey, including increasing rates of confusion between sources, but they also provide the ability to use subsets of the data to construct higher resolution images due to the large number of repeat observations. These properties allow investigations of galaxies of brightness which are close to the noise floor in the main survey. Having an accurate error model is essential for optimal photo-z performance; the larger number of repeat observations in the Deep Drilling Fields enables empirical checks on the magnitude and flux uncertainties generated by the LSST pipeline, through both higher signal-to-noise stacks and using subsets of the data to model the uncertainties. As LSST imaging data will not be available for several more years, such studies of subset stacks to examine seeing and error properties would have to use pre-existing data sets, e. g. HyperSuprimeCam data, when testing such algorithms and putting needed infrastructure in place so that it can be used once LSST data is flowing.

In addition to providing useful information about main-survey photometric redshift quality, the Deep Drilling Fields will pose particular challenges for photometric redshift determination, as spectroscopy for complete samples down to the DDF depth for photo-z training and calibration will be completely infeasible, and the DDF area is likely too small for high-precision calibration by cross-correlation techniques.

Activities: Tests of confusion limits in deeper coadds than available in the main survey, as well as improvements enabled by ”best seeing” subsamples on precursor data sets. Tests of the flux error model using subsets and higher signal-to-noise coadds.

Deliverables:
(a) Studies of confusion and deblending in deep stacks and “best seeing” conditions using precursor data sets.
(b) Estimates of gains in studying faint galaxy populations at higher signal-to-noise than available in the main survey.
(c) A check on LSST flux error models using both higher signal-to-noise coadds and subsets of the data to main survey depth using precursor data sets.

3.7.3 Multivariate Physical Properties of Galaxies from Photometric Redshifts

PZ-3. *Motivation:* Measurements of key derived physical properties are critical for much work on galaxies and their evolution. The properties measurable from SEDs include star formation rate (SFR), stellar mass ($M_\star$), specific SFR (sSFR), dust attenuation, and stellar metallicity.

Many recent science analyses have relied upon derived physical properties rather than fluxes and luminosities in the UV, optical and near-IR bands. This is largely a matter of convenience: utilizing tables of derived properties require no redshift (K) corrections or extra dust corrected, as those are effectively applied in the measurement process; they are also closer to the quantities best determined in simulations. However, derived quantities have the disadvantage of the potential for significant systematic errors in measurement, as well as non-uniformity in their definition (e.g., differences in adopted IMF can change stellar masses by ~ 0.5 dex).

Stellar mass has emerged as a parameter of choice for selecting galaxy samples and attempting to make apples-to-apples comparisons of galaxies at different redshifts. The sSFR (current SFR normalized by stellar mass) provides a measure of a galaxys star formation history. Dust attenuation and stellar metallicity can help to probe processes important for understanding galaxy evolution.

This Task shares some goals with the Dark Energy Science Collaboration Photometric Redshifts working group, as laid out in their Science Roadmap (see 3.7.1:PZ-1 footnote for document link), who are also interested in multidimensional probability density functions joint in redshift and stellar mass, star formation rate, and dust content of the galaxies. Coordination on this area with the DESC Photo-z working group will benefit both groups.

Activities: Deriving physical properties, usually accomplished by spectral energy distribution (SED) fitting, is an involved process and the results depend on a number of factors, including the underlying population models, assumed dust attenuation law, assumed star formation histories, choice of model priors, choice of IMF, emission line corrections, choice of input fluxes, type of flux measurements, treatment of flux errors, SED fitting methodology, and interpretation of the resulting probability distribution functions (PDFs; e.g., Salim et al., 2016).

In the case of LSST, an additional challenge is that the redshifts available will generally be photometric, and carry a PDF (a measure of uncertainty) of their own. In principle, the redshift and SED (or specific physical parameter) should be determined simultaneously, as the inferred galaxy properties such as luminosity and stellar mass are correlated with redshift. One alternative approach is to estimate the redshift PDF using empirical training sets, then estimate best fitting SEDs at each redshift to determine physical parameters. This approximation enables the use of potentially more accurate machine learning based methods to estimate the redshift PDF, at the possible expense of adding biases and degeneracies due to the assumptions inherent in treating the redshift and physical properties separately. Further study is necessary to determine whether the benefits of this approximation outweigh the drawbacks. Activities will consist of testing whether the determination of physical parameters and photo-z should be performed jointly or not, based on training sets with spectroscopic redshifts at a range of redshifts.

Deliverables:

(a) Pre-LSST: A set of guidelines as to optimal practices regarding the derivation of both the photo-z

and properties, together with the software to be used.

(b) With LSST data: in consultation with the DESC Photo-z working group, the production of catalogs of properties to be used by the collaboration.

3.7.4 Identifying Spectroscopic Redshift Training Sets for LSST

PZ-4. *Motivation:* Accurate photometric redshift estimates require deep spectroscopic redshift data in order to help train algorithms, either directly in the case of machine learning based algorithms, or to train Bayesian priors and adjust zero points, transmission curves, or error models for template-based methods. Representative spectroscopic samples can be used to investigate the accuracy of photo-z algorithms. Obtaining representative training sets is a problem across multiple science tasks, and in fact, across many current and upcoming large surveys. As the telescope resources necessary will be quite extensive, coordination with the other large surveys is essential. A detailed study of spectroscopic training needs and potential spectroscopic instruments that will be available in the coming years was undertaken by Newman et al. (2015). We must now begin our attempts to obtain the necessary samples. We must also identify any needs that are unique to galaxy science that may not be prioritized in the cosmology-focused efforts to date, e. g. are faint galaxy populations sampled adequately in the planned spectroscopic samples?

Activities: In coordination with other large surveys, collate existing spectroscopic redshift data over both DDF and wider fields, and assess the biases due to selection and redshift incompleteness for each spectroscopic data set. Assess the robustness of existing data, and determine color spaces where existing surveys lack statistics. Apply for additional spectroscopy to fill in parameter space not already covered by existing surveys. This work should become much more efficient once PFS and MOONS become available.

Deliverables:

(a) A list of existing *robust* spectroscopic objects, and identified gaps in the currently available training samples.

(b) Telescope proposals for spectroscopic campaigns to fill in the sample gaps.

3.7.5 Simulations with Realistic Galaxy Colors and Physical Properties

PZ-5. *Motivation:* As representative samples of spectroscopic redshifts will be very difficult to compile for LSST, simulations will play a key role in calibrating estimates of physical properties such as galaxy stellar mass, star formation rate, and other properties. This is particularly problematic for photometric surveys, where photometric redshift and physical property estimates must be calculated jointly. In addition, we must include prominent effects that will influence the expected photometric performance; for example, the presence of an active galactic nucleus can significantly impact the color of a galaxy and the inferred values for the physical parameters, so models of AGN components of varying strength must also be included in simulations.

Many current-generation simulations cannot or do not simultaneously match observed color distributions and physical property characteristics for the galaxy population at high redshift. As photo-z algorithms are highly dependent on accurate photometry, realistic color distributions are required to test the bivariate redshift-physical property estimates. Working with the galaxy simulations and high redshift galaxy working groups to develop new simulations with more accurate high redshift colors is a priority. These photo-z needs are not unique, and the improved simulations will benefit both the Galaxies Collaboration and other science collaborations. Indeed, one fruitful way to proceed with this work may be to incorporate new tests into the DESCQA framework being used by the LSST Dark Energy Science Collaboration to improve mock catalogs for DESC work (Mao et al. 2017, in prep.).

Activities: The main activity for this task is to develop improved simulation metrics based upon observational studies of both low- and high-redshift galaxies. This will require expertise from the photo-z high-redshift galaxies, AGN, and simulations working groups. In order to test whether mock galaxy populations agree with the real Universe, we must have some real data to compare against, even if it is a luminous subsample or only complete in certain redshift intervals. Once such comparison datasets are established, metrics can be developed to determine which simulations and simulation parameters most accurately reproduce the observed galaxy distributions.

If we then assume that the simulations are valid beyond the test intervals, we can use them as a testbed to develop improved algorithms for a wide variety of applications, e. g. selecting specific sub-populations of galaxies. One key aspect of this work is that spectral energy distributions in simulations cannot be generated from discrete templates, but instead must span a continuous range of properties. If only a finite set of restframe SEDs are used in the simulation, the photo-z problem would be unnaturally simplified and falsely strong photometric redshift predictions would result. Thus a method is required that simultaneously reproduces galaxy colors without resorting to a restricted set of SEDs. For example, this could be done by creating complete SEDs based on an extended set of principal components (e.g., extending the *kcorrect* or EAZY basis set), though in general additional constraints are required with PCA-like techniques to ensure that unphysical spectra are not generated.

With sufficiently realistic simulations that reproduce the ensemble of galaxy star formation histories and the mapping between those histories and spectral energy distributions, we can use simulated catalogs to test techniques for identifying specific galaxy sub-populations. For some studies, we may wish to examine the relationship between galaxies in specific sub-populations and their large-scale structure environment. Thus, realistic density and clustering properties are also important in the simulation. There are a wide variety of techniques that may be used for environmental measures, operating on a variety of scales. As small-scale measurements can be noisy and/or washed out by photometric redshift errors, it may be more effective to measure the average overdensity/environment as a function of galaxy properties, rather than the reverse.

Deliverables:

(a) Determination of a list of which physical parameters are important for galaxy science.
(b) Compiling observable datasets that can be used as comparators for simulated datasets.
(c) Developing a set of metrics to compare simulations to the observational data. These may be implemented in the DESCQA framework.
(d) Use the metrics in deliverable B to create updated simulations with more realistic parameter distributions.
(e) Development of improved joint estimators for redshift and physical properties (M*, SFR, etc.).
(f) Development of improved spectral extended basis sets to create galaxy colors which match observations, including emission lines, etc.
(g) Using mock catalogs, developing techniques that for selecting specific galaxy sub-samples.

(h) Developing environment estimators for simulated datasets and algorithms able to measure the strength of environmental dependence on galaxy properties.

3.7.6 Incorporating Galaxy Size and Surface Brightness into Photometric Redshift Estimates

PZ-6. *Motivation:* Photometric redshift algorithms most commonly have used galaxy fluxes and/or colors alone to estimate redshifts. However, morphological information on a galaxys size, shape, overall surface brightness (SB), or detailed surface brightness (SB) profile can provide additional information that can aid in constraining the redshift and/or type of a galaxy, breaking potential degeneracies that using colors alone would miss. Gains can be particularly substantial at low redshift where LSST will at least partially resolve galaxies. Incorporating morphological information may help to improve joint predictions for galaxy properties and redshift as well, at the cost of imposing assumptions about links between morphology and color/SED that may not apply to all galaxies. If sufficient training samples are available, priors for redshift and SED parameters given morphological parameters, $p(z, SED|P)$, can be constructed that can be incorporated into Bayesian analyses of photometric redshifts and potentially lead to improved constraints on the redshift PDF (i.e., $p(z|P,C)$, where P represents observed morphological parameters, C represents observed flux/color measurements, and SED represents one or more parameters representing the restframe SED of a galaxy).

Activities: The first activity for this task will be to assess whether LSST Data Management algorithms for multiple-Sersic model fits to galaxy photometry are sufficient for the needs of this working group. Evaluation of DM pipeline-processed precursor datasets in regions with HST imaging may be particularly valuable. With measures of morphological parameters in hand, a useful next step would be to evaluate whether photometric redshift estimates in fact improve with the incorporation of morphological information (in the domain where training is perfect, i.e., with training sets and test sets with matching properties); this may be done using machine learning-based codes, which can make maximal use of all information available in the parameter set provided without requiring the development of a detailed model (such methods extrapolate poorly, but that is not a problem for this test). If incorporating morphological information does in fact yield improvements, the next step would be the development of Bayesian priors for redshift given galaxy photometry and morphology measurements for incorporation into template-based methods. This may be done using either pipeline-processed simulated datasets (if they are sufficiently realistic) or real observations with spectroscopic redshifts. Tests will then show the performance of photometric redshifts incorporating morphological priors relative to performance using galaxy photometry alone.

Deliverables:

(a) Tests of LSST DM algorithms for measuring morphological parameters for galaxies.
(b) A cross-matched catalog containing objects with known redshifts and DM pipeline-measured morphology measurements.
(c) Tests of whether incorporating morphological information improves photometric redshift measurements using machine learning-based algorithms, as well as examination of what parameters are most informative
(d) Bayesian priors $p(z, SED|P)$ that can be incorporate into template-based algorithms and used to improve photo-z measurements.

3.8 Theory and Mock Catalogs

A critical challenge for interpreting the vast LSST dataset in the context of a cosmological model for galaxy formation involves the development of theory, both in the practical applications of realistic simulations and the engineering of new physical models for the important processes that govern the observable properties of galaxies. The following preparatory science tasks for LSST-related theoretical efforts range from understanding the detailed properties of galaxies that LSST will uncover to predicting the large-scale properties of galaxy populations that LSST will probe on unprecedented scales.

3.8.1 Image Simulations of Galaxies with Complex Morphologies

TMC-1. *Motivation:* LSST images will contain significant information about the dynamical state of galaxies. In principle, we can exploit this morphological information to learn about the formation and evolutionary histories of both individual and populations of galaxies. Examples of important morphological features include spiral arms, tidal tails, double nuclei, clumps, warps, and streams. A wide variety of analysis and modeling techniques can help determine the past, present, or future states of observed galaxies with complex morphologies, and thereby improve our understanding of galaxy assembly.

Activities: Activities include creating synthetic LSST observations containing a wide variety of galaxies with complex morphologies, for the purpose of testing analysis algorithms such as de-blending, photometry, and morphological characterization. Supporting activities include creating databases of galaxy images from models (such as cosmological simulations) or existing optical data, analyzing them using LSST software or prototype algorithms, and distributing the findings of these studies. These analyses may involve small subsets of the sky and do not necessarily require very-large-area image simulations or need to match known constraints on source density. Results will include predicting the incidence of measured morphological features, optimizing Level 3 measurements on galaxy images, and determining the adequacy of LSST data management processes for these science goals.

Deliverables:

(a) Creating synthetic LSST images of galaxies with complex morphology from simulations.
(b) Creating synthetic LSST images based on prior observations in similar filters.
(c) Making LSST-specific complex galaxy data products widely available.
(d) Publicizing results from algorithm tests based on these LSST simulations.
(e) Assessing Level 3 measurements to propose and/or apply in maximizing the return of LSST catalogs for complex galaxy morphology science.

3.8.2 New Theoretical Models for the Galaxy Distribution

TMC-2. *Motivation:* Meeting the challenge of building synthetic, computer-generated mock surveys for use in the preparation of extragalactic science with LSST will require the assembly of experts in key theoretical areas. LSST will collect more data than contained in the current largest survey, the SDSS, every night for ten years. The analysis of such data demands a complete overhaul of traditional techniques and will require the incorporation of ideas from different disciplines. Mock catalogs offer the best means to test and constrain theoretical models using observational data, and play a well-established role in modern galaxy surveys. For the first time, systematic uncertainties will limit the scientific potential of the new surveys, rather than sampling errors driven by the volume mapped. A variety of viable, competing cosmological models already provide only subtly discernable signals in survey data. Distinguishing between the models requires the best possible theoretical predictions to understand the measurements and their subsequent analysis, and to understand the uncertainties on the measurements.

Activities: Develop a new state-of-the-art in physical models of the galaxy distribution by combining models of the physics of galaxy formation with high resolution N-body simulations that track the hierarchical growth of structure in the matter distribution. The key task involves performing moderate volume cosmological N-body simulations, generating predictions from an associated model of galaxy formation, and then embedding this information into very large volume simulations that can represent LSST datasets. The large volume simulations will extend beyond the volume of the target survey, allowing a robust assessment of the systematic uncertainties on large-scale structure measurements.

Deliverables:
(a) Physically motivated mock galaxy catalogues on volumes larger than those sampled by LSST, with a consistently evolving population of galaxies.
(b) Base catalogues of dark matter haloes and their merger trees suitable for use by theoretical models for populating these with galaxies (halo and subhalo occupation/abundance matching techniques).
(c) Small volume simulations for further tests of baryonic physics and detailed observational comparisons.

3.8.3 Design of New Empirical Models for the Galaxy Distribution

TMC-3. *Motivation:* The galaxy-halo connection represents the end state of the combined physics of baryonic galaxy formation and dark matter structure formation processes. A full exploitation of the LSST dataset for understanding galaxy formation will necessarily involve the exploration of the galaxy-halo connection, using the simulations of the galaxy formation process to build better empirical models. Empirical models can adjust to reproduce observational results as closely as possible, whereas computationally expensive physical models often prove too expensive to tune in the same manner. Empirical models also have the advantage of being extremely fast, allowing large parameter spaces to be explored.

Activities: Developing models of the galaxy-halo connection for LSST require two main stages. The first step tests current empirical models to judge the fidelity with which they reproduce the predictions of physical models based on simulations. The second step uses physical models to devise new parameterizations for empirical models to describe galaxy populations for which little or no data yet exists, providing enhanced empirical models relevant for upcoming surveys that will probe regimes that remain largely unmapped.

Deliverables:
(a) Predictions for the evolution of clustering from physical models.
(b) Enhanced paramertizations for empirical models with reduced freedom, greater applicability, and more rapid population of catalogs to describe the observer's past lightcone.

3.8.4 Estimating Uncertainties for Large-Scale Structure Statistics

TMC-4. *Motivation:* The ability to interpret the relation between galaxies and the matter density field will depend critically on how well we understand the uncertainties of large-scale structure measurements. The accurate estimation of the covariance on a large-scale structure measurement such as the correlation function would require tens of thousands of simulations.

Activities: Devise and calibrate analytic methods for estimating the covariance matrix on large-scale structure statistics using N-body simulations and more rapid but more approximate schemes, such as those based on perturbation theory. Coordinate with Dark Energy Science Collaboration Working Groups, as these covariance matrices can also inform Cosmological parameter constraints.

Deliverables:

(a) Physically motivated estimates of covariance matrices for galaxy occupation (and other) parameter searches.

3.9 Auxiliary Data

While LSST will produce outstanding quality optical imaging with temporal spacing, a significant amount of additional science will be enabled through the combination of these data with existing and upcoming external datasets; both spectroscopic (*i.e.*, redshift and/or spectral line measurements) and panchromatic (*i.e.*, x-ray, UV, IR, radio photometry). However, bringing together these external datasets into a useable, coherent, and quality controlled format is non-trivial and requires significant effort. In particular, the number, size and complexity of both *spectroscopic* and *panchromatic* datasets is likely to dramatically increase with the advent of a number of new ground and space based facilities. Both in preparation for and during LSST operations it is therefore prudent to ensure appropriate access, usability, and quality control of external datasets are in place via the establishment of an auxiliary LSST database.

3.9.1 Extragalactic Optical/NIR Spectroscopy within the LSST Footprint

AUX-1. *Motivation:* Although great strides have been made in projects using photometric redshifts alone, some science is only possible with either spectroscopic redshifts and/or spectroscopic line measurements. In particular, spectroscopic redshifts are essential when distance accuracies of less than 1000 km/s are required; for example in identifying galaxy pairs and groups. Robust measurement of gas and stellar phase metalicities also require relatively high-S/N spectra (3 to 20 respectively) at a spectral resolution of better than a few Angstroms. Finally, photometric redshifts still require spectroscopic redshifts for both calibration and accuracy assessment. As such, it is essential that we ensure the LSST community has access to the available high precision redshifts, spectroscopically-derived properties and calibrated spectra for all available galaxies and quasars within the LSST footprint. This necessarily entails bringing together data from disparate surveys (such as 2dFGRS, SDSS, 6dF, MGC, GAMA, VIPERS, VVDS), the homogenization of data products and quality control, as well as the ongoing ingestion of upcoming spectroscopic campaigns such as TAIPAN, DEVILS, MOONS, 4MOST, DESI, PFS, Euclid etc. This will require significant pre-LSST effort.

Activities: Several activities are necessary to compile this spectroscopic database:

(a) Establishment of a database structure capable of accommodating and serving both spectra and derived data products including fast SQL database queries.
(b) Ingestion of existing key public datasets including, for example: 2dFGRS, SDSS, 2QZ, 2SLAQ, 6dF, MGC, GAMA, ESP, VVDS, VIPERS.
(c) A process for establishing quality control and homogenization of datasets including assignment of revised quality flags.
(d) A pathway for ingesting future datasets as they become available and potentially in advance via MOU arrangements, e.g., TAIPAN, DEVILS, MOONS, 4MOST, DESI, PFS, Euclid, etc.

Approximately 6 million spectroscopic redshifts are known, with the majority of these already in the public domain; along with associated flux and wavelength calibrated spectra. In addition, derived parameters also exist for many of these spectra including, but not limited too, redshifts, equivalent widths, velocity dispersions, line asymmetries etc. Many of these measurements have been made using bespoke software specific to each originating survey (e.g., SDSS v 2dFGRS), creating an inhomogeneous network of data, measurements and quality control flags within the LSST footprint. In addition, in the next decade a number of new surveys will expand these measurements from millions to tens of millions of spectra through facilities and programs such as LAMOST, 4MOST, DESI as well as coarse spectroscopic information via GRISM data from Euclid and eventually WFIRST, leading to a wealth of spectroscopic data which will be invaluable to LSST. The community has two specific problems, i) collating this data and ii) ensuring quality control and standardization. Due to differing observing and analysis techniques not all spectroscopic measurements will be equal, and will depend on the resolution, signal-to-noise and precise software applied. Within reason some effort should be made to both collate and standardize the data with some provision of a uniform quality control process. At the bare minimum this should result in a database which contains the flux and wavelength calibrated spectra, links or copies of original derived products, and crucially, measurements using a uniform set of software analysis tools (e.g., to produce consistent redshift and equivalent width measurements) with some coherent cross-survey quality control flags. While this task sounds intimidating, this is exactly what has been achieved within the 200 square degrees of the Galaxy And Mass Assembly survey (Driver et al., 2011, 2016; Liske et al., 2015) and an expansion of this process to the full LSST footprint is not unreasonable or impossible. However, this process needs to commence imminently if the database is to be in place for both LSST and the next generation of spectroscopic surveys. As the majority of LSST's footprint covers the Southern Hemisphere, where many (but not all) large spectroscopic surveys have been instigated from Australia, this task represents a potential contribution from the Australian LSST contingent.

Deliverables:
(a) A useable and searchable database of spectra with associated derived products.
(b) Derived products using standardized analysis codes to measure redshifts and equivalent widths, etc.
(c) A strategy for ingesting additional datasets as they become available.

3.9.2 Panchromatic Imaging within the LSST Footprint

AUX-2. *Motivation:* LSST will only cover a small portion of the electromagnetic spectrum emanating from stars and accretion disks around supermassive black holes. In understanding the galaxy life cycle we inevitably require observations of the full gas-stars-dust cycle along with additional processes from AGN and dust attenuation. As such, many LSST science goals will require access to the best available x-ray, UV, IR, and radio data. While archives of these data exist independently, there is a dire need to establish a Universe database which federates these data in a coherent manner. One of the major concerns of such a database is the accurate multi-wavelength source identification and de-convolution in disparate data with wildly differing resolutions. For example, two closely separated sources in the LSST data may appear as a single source in lower resolution data. As such, significant errors will be made when simply table matching these photometric catalogues. The unavoidable solution to this problem is to bring the data into a single repository and allow sophisticated codes (*e.g.*, TFITs; LAMBDAR etc.) to determine appropriate flux measurements with associated errors based on apertures defined in high-resolution (LSST or other) bands. This will be particularly important as we extend to x-ray and radio wavelengths where the radiation fundamentally arises from spatial locations which are aligned with, but not identically co-incident to, the optical radiation (*e.g.*, diffuse HI envelopes, diffuse x-ray halos, discrete x-ray sources and extended radio lobes).

Activities: Several activities are required:
(a) Database to host imaging data from diverse sources, including astrometric alignment.
(b) Software to define aperture in a specified (LSST) band.
(c) Software to measure flux across panchromatic data taking into account original aperture definition, facility resolution, signal-to-noise limitations, and any physical priors.
(d) Tools to serve imaging and photometric data either for individual or sets of objects.

As galaxies emit radiation across the entire electromagnetic spectrum it is important to be able to trace this breadth of emission deriving from different astrophysical processes. This is particularly important in the LSST optical wavebands where anywhere from 0-90 per cent of the radiation might be attenuated by dust and re-radiated in the far-IR. The robustness of photometric redshifts also relies on folding in non-optical (i.e, UV, near-IR and mid-IR) priors to minimize ambiguities between, for example, the Lyman- and the 4000Ang-breaks. Moreover robust photometric redshifts also require consistent and accurate error estimates which cannot be guaranteed when using table matched data produced by different groups using different methodologies. Finally, x-ray and radio facilities that have traditionally focused on the AGN population. However, other processes are now becoming increasingly relevant as they extend to deeper observations (such as those with SKA-precursors and eROSITA) and become sensitive to both extended emission and/or emission related to star-formation. Unification across the wavelength range requires federation of these very disparate datasets. This will become an increasingly common problem as we move into the ear of Big Data, and hence is worth centralizing prior to LSST operations. Note a similar task has recently been achieved by the Galaxy And Mass Assembly team for a 200 square degree region (see Driver et al., 2016, and http://www/gama-survey.org/) and can be extended to the full LSST footprint using similar techniques.

Deliverables:

(a) A database capable of serving image cutouts at any location over the LSST footprint and any wavelength (see http://cutout.icrar.org/psi.php for a similar database over the GAMA regions). This database should include
- X-ray maps from eROSITA
- UV from GALEX
- Optical from SkyMapper, DES, and Euclid.
- Near-IR from VISTA and Euclid.
- Mid-IR from WISE.
- Far-IR from IRAS, Herschel, and Spica.
- Radio continuum and HI from ASKAP (EMU,WALLABY,DINGO), MeerKAT (LADUMA, MIGHTEE, MeerKLASS), and eventually the SKA.

(b) Derived panchromatic photometry (on the fly or pre-processed).

3.9.3 Tully-Fisher Measurements Combining LSST and SKA Pathfinders

AUX-3. *Motivation:* How do galaxies evolve kinematically? The relation between stellar luminosity and rotation for disk galaxies is well known in the local Universe (i.e., the Tully-Fisher or T-F relation, see Tully & Fisher, 1977; Verheijen, 2001) and suspected to evolve as gas and stars form a disk within the dark matter gravitational potential. H I extends throughout the stellar disk and well beyond, its kinematics tracing the galaxy's dark matter potential. How the T-F relation evolved with cosmic time and redshift is being debated; whether the normalization or the slope or both evolve (Weiner et al., 2006; Tiley et al., 2016b)? A few major drawback for these studies into the evolution of the T-F are (a) the kinematic information comes from Hα optical data (sometimes redshifted into the infra-red, which does not trace the full rotation curve, (b) adaptive optics for these observations filters out the lower surface brightness features such as the rotating disk (see for a review Glazebrook, 2013), and (c) these measurements are made for intrinsically bright samples of galaxies. However, some progress can be made by stacking low signal-to-noise H I spectra using an optical prior (Meyer et al., 2016).

The $z = 0$ calibration however is very solid with large samples (e.g. Ponomareva et al., 2016; Tiley et al., 2016a), detailed kinematics (Trachternach et al., 2008), extending down to low mass galaxies (McGaugh et al., 2000; Oh et al., 2015). The first deep, higher redshift observations have been made but are still limited in scope and samples sizes (Verheijen et al., 2010; Fernández et al., 2013, 2016).

For a Tully-Fisher measurement, one needs a kinematic measurement (preferably through H I measurement), an accurate photometry measurement, and a disk inclination. The last two critical measurements will be provided by LSST imaging. There are two main MeerKAT surveys that offer the opportunity for synergy with the LSST galaxy photometry: the MeerKAT International GigaHertz Tiered Extragalactic Exploration (MIGHTEE, Jarvis, 2012) project and the Looking At the Distant Universe with the MeerKAT Array (LADUMA, Holwerda & Blyth, 2010; Holwerda et al., 2011, Blyth+ *in prep.*). Both target H I observations in the LSST confirmed deep drilling fields and thus offer the opportunity to explore the Tully-Fisher relation out to redshift $z \sim 1$ through direct detecton and possibly stacking. MIGHTEE and LADUMA represent the deepest two tiers of the H I survey strategy for the combined pathfinder instruments.

Two other surveys represent the progressively wider/shallower H I survey tiers with the ASKAP telescope (Johnston et al., 2007): DINGO, a survey of the GAMA fields (Driver et al., 2009; Duffy et al., 2012; Meyer et al., 2015, Meyer+ *in prep*) and WALLABY, the Southern Sky H I survey (Duffy et al., 2012, Koribalski+ *in prep*). A benefit of the MeerKAT and ASKAP radio surveys is that they are conducted commensally: radio continuum and 21 cm emission line (H I) are observed at the same time. The combination The survey strategy from wide and shallow to single deep field (WALLABY-DINGO-MIGHTEE-LADUMA) is designed to beat down cosmic variance effectively (see e.g., Maddox et al., 2016).

Activities: Several activities are necessary to compile kinematic evolution using a combination of H I kinematics and LSST imaging:

(a) Accurate photometry of extended objects in all LSST deep drilling fields.
(b) accurate morphology of all galaxies with HI detections (to infer inclination).
(c) Spectroscopic redshifts of all galaxies *not* detected in H I for stacking purposes.

Deliverables:

(a) Robust and accurate inclination estimates from morphological fits/models.
(b) Accurate galaxy photometry from deep drilling stacks.
(c) Stacking code for H I spectra.

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