Large Synoptic Survey Telescope Galaxies, Dark Matter, and Black Holes: Extragalactic Roadmap

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Abstract.

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1 Introduction

The Large Synoptic Survey Telescope (LSST) is a wide-field, ground-based telescope, designed to image a substantial fraction of the sky in six optical bands every few nights. It is planned to operate for a decade allowing the stacked images to detect galaxies to redshifts well beyond unity. The LSST and the survey are designed to meet the requirements (Ivezic & the LSST Science Collaboration 2011) of a broad range of science goals in astronomy, astrophysics and cosmology. The LSST was the top-ranked large ground-based initiative in the 2010 National Academy of Sciences decadal survey in astronomy and astrophysics, and is on track to begin the survey early in the next decade.

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 been instrumental in helping to develop the science case for LSST (encapsulated in the LSST Science Book), to refine the concepts for the survey and for the data processing, and to 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 that will need to be overcome to realize LSSTs potential for measuring the effects of Dark Energy. They looked at five complementary techniques for tackling dark energy, and outlined high-priority tasks for the science collaboration during construction. They designated sixteen working groups (some of which already existed) to coordinate the work. This roadmap has been documented in a 133-page white paper (arxiv.org/abs/1211.0310). The white paper provides a guide for investigators looking for ways to contribute to the overall investigation. It may help in efforts to obtain funding, because it provides clear indication of the importance of the advance work and how the pieces fit together.

The investigation of Dark Energy is only one topic for LSST. It is important to develop similarly concrete roadmaps for work in other areas. After some discussion among the collaborations, it appears useful in some cases for different science collaborations to join forces on a single whitepaper. This is particularly true for topics that involve observations of distant galaxies. With the advent of the DESC, some of the science goals of the large-scale-structure, weak-lensing, and strong-lensing collaborations have found a new home. The remaining science goals of those collaborations tend to be focused on galaxy evolution and dark matter. Two other collaborations: AGN and Galaxies, also have those topics as major themes. This roadmap identifies the major high-level science themes of these investigations, outlines how complementary techniques will contribute, and identifies areas where advance work is essential. For this advance work, the emphasis is on areas that are not adequately covered in the DESC roadmap. As convenient shorthand, we use the acronym GALLA (Galaxies, AGN, Lensing Large-scale Structure and Astro-informatics) joint roadmap of the overlapping science collaborations.

Chapter 2 gives a brief summary of the science background. Many of the themes and projects are already set out in the Science Book, where more detail is provided for many of the science investigations. Chapter 3 sets out the highest priority preparatory work to enable these investigations. These tasks are laid out on the assumption that the work plan of the DESC will be carried out and that software and data products resulting from that work will be available to other science collaborations. The Appendix 4 organizes the tasks by science topic and desribes them in more detail.

2 Science Background

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2.1 Overview

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2.2 Science Background: AGN

2.3 Science Background: Galaxies

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.

The Large Synoptic Survey Telescope (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 provide both an unequaled catalogue of billions of extragalactic sources and high-quality multiband imaging of individual objects. This section of the *Extragalactic 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 any 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.

2.3.1 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 (*ugrizy*), 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 $\lambda \approx 4000\AA$ 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. 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, 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 $30,000$ 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.

2.3.2 Galaxies as Cosmic Structures

The structural properties of galaxies arise from an intricate combination of important astrophysical processes. 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.

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, stellar mass, and luminosity. Morphological studies will employ at least two 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). 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 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, the 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. Observational measures of the outer most regions of thin disks can constrain 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 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 ability of LSST to probe low surface brightnesses also allows for characterization of stellar halos that surround nearby galaxies. Structures in stellar halos, from streams to density inhomogeneities, originate from the hierarchical formation process and their morphology provides clues to the formation history on a galaxy-by-galaxy basis (Bullock & Johnston 2005; Johnston et al. 2008). Observations with small telescopes (Martínez-Delgado et al. 2008; Abraham & van Dokkum 2014) have already demonstrated that stellar halo structures display interesting variety (e.g., van Dokkum et al. 2014). LSST, with its unrivaled entendue, can help build a statistical sample of stellar halos and cross-reference their morphologies with the observed properties of their central galaxies. Such studies may determine whether the formation histories reflected in the structures of halos also influence galaxy colors or morphological type. The examination of stellar halos around external galaxies may also result in the identification of small mass satellites whose sizes, luminosities, and abundances can constrain models of the galaxy formation process on the extreme low-mass end of the mass function.

2.3.3 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, mutliband imaging, and depth) to investigate this long-standing problem.

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.

Lastly, 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., Conselice et al. 2003; Kartaltepe et al. 2007; Lotz et al. 2008; Lin et al. 2008; Robotham et al. 2014). 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.

2.3.4 Science Book

The contents of the Galaxies Chapter 9 of the Science Book (Abell et al. 2009).

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

2.4 Science Background: Astroinformatics

2.5 Science Background: Large Scale Structure

2.6 Science Background: Strong Lensing

2.7 Science Background: Weak Lensing

3 The Roadmap

4 Task Lists by Science Area

In this Appendix, we identify specific areas where effort is needed to prepare for LSST science. Tasks are categorized as (1) *techniques algorithms, techniques, or software*, (2) *precursor observations or synergy with other facilities*, (3) *LSST-targeted theory or simulations* and (4) *Databases, science queries and data services.* For convenience in preparing the Appendix, these are divided by science topic along the science collaboration boundaries. The lists in this Appendix were synthesised and consolidated in the roadmap in chapter 3.

4.1 Black Hole Science Preparations

This document is a draft road-map for Black Hole science with LSST. Here we describe the broad "to do" list that defines the roadmap for all BH science, in addition to focusing on tasks needed for certain science cases and also areas where the needs of this group may overlap with roadmap plans from other groups. In composing it, I have followed the organization of the LSST Science Book, specifically Chapter 10 on AGNs. That way the authors of the sub-sections can clearly identify any issues that we have (so far) failed to address herein.

4.1.1 AGN Selection and Census

Black Hole (BH) science will be a major theme for LSST covering science topics ranging from the BH-fueled evolution of galaxies, to lensed black holes as tools for cosmology, to small-scale physics of the BHs themselves using variability and tidal disruptions as probes. For all BH science with LSST the first step that must be taken is to find the BHs themselves, whether through short-lived transient events or longer-lived fueling. In that sense the primary goal for this roadmap for BH science is seemingly straightforward: identify efficient and complete ways to pinpoint the location of black holes on the sky, and, ideally, their redshifts. In practice the devil is in the details and the optimal solution to this problem may be different for each of the LSST's BH science goals.

In the past, BH science could afford low efficiency in candidate selection because of spectroscopy: even if the majority of targets were not BHs, at least that was known. Today, while we can hope for a significant amount of spectroscopy from DESI and/or similar projects, it is clear that we will not obtain spectroscopy for tens of millions of candidate BHs. Thus we need to concentrate on going it alone. In simplest terms this means identifying BHs with both high completeness and high efficiency.

Unfortunately the optimal methods for doing so are not expected to be generic for all BH science. Broadly speaking LSST BH science can be divided into the need to identify four types of BHs: unobscured quasars, obscured quasars/AGNs, lower-luminosity AGNs, and transient BH fueling events. This is further complicated by the fact that objects in each category may require somewhat different methods as a function of redshift and/or by (close) spatial separation.

For example, selection of unobscured quasars can take full advantage of the LSST data set: multi-band, multi-epoch optical photometry and astrometry, whereas selection of obscured quasars necessarily relies on supporting data from outside LSST. Lower-luminosity AGNs will further need to be weeded from (the far more abundant) inactive galaxies, and identification of transient-fueled BHs will be limited by the number of epochs of detection. Each of these cases do have a similar task need: developing new tools and applying them to simulated data.

For unobscured quasars we must optimize the identification of BHs using

- colors
- variability
- astrometry

—ideally all three simultaneously. Moreover, we will have to consider the impact of star-galaxy separation (can we use the same algorithm(s) regardless of morphology?) and the evolution of these properties with redshift.

For obscured quasars, we will necessarily be reliant upon information from other sources to confirm the "active" nature of what will otherwise appear as normal galaxies (or not appear at all) in LSST.

Without a doubt one of the single most important to do items in terms of LSST AGN selection is to run simulations that use all 6 LSST bands, covering as much area and as many epoch as possible. Such simulations should also include as much physics and empirical correlation as possible. This includes: luminosity-dependence of emission features, magnitude-color correlations, variability physics, astrometric errors, differential chromatic refraction, nuclear vs. host galaxy luminosity correlation [and its relationship to morphology], star-galaxy separation, lensing probability, broad absorption lines and dust reddening (intrinsics, host galaxy, and intervening). These simulations already exist and are relatively mature, but new simulated data has not been produced in a number of years and the simulations have not been fully vetted by the science collaborations. One or more groups will need to begin running the simulation code and conducting various tests (e.g., comparing to real data).

Lastly, a goal for LSST should be for every science working group to give a probability for *every* LSST object. This information can then be fed back into the classification schemes developed by each group. E.g., an object that the AGN group gives a 30% chance of being an AGN might be downgraded if the SNe group flags it as an SN at 99%.

Color Selection

Color-selection by itself is certainly the most mature of the avenues for identifying AGNs. Any application of modern statistical techniques such as described by [take REFS from Tina's paper] will be a major first step in the process.

Specific to do items in this regard are to establish an agreed-upon test bed of color data and have a "bake off" to determine which methods are the most effective. This could include (or be completely based upon) simulated data.

Moreover, it is unlikely that any final method(s) adopted for LSST AGN selection will be completely color based, thus it will be important to extend such efforts to multi-parameter selection methods using the information from the next sections.

Isolation of *nuclear* colors through difference imaging may be crucial for low-luminosity systems (which will provide the bulk of new LSST discoveries).

Lack of Proper Motion/Astrometry

As certain quasars and stars can have very similar colors, the fact that quasars do not have proper motions as do Galactic stars has long been used as a discriminant. That will be no different for LSST. However, even with its precise astrometry, LSST will need to distinguish between objects that are only apparently moving and those that are truly moving and do so as a function of apparent magnitude. Simulated data can be used to start this process.

Another task that can begin now is to extend algorithms that use USNO data as a time baseline extension to new data from GAIA. Stripe 82 data can be used as an LSST-like testbed for this.

A more recent approach has been to take advantage of differential chromatics refraction of AGNs (Kaczmarczik et al. 2009). In short this procedure makes use of the astrometric offset of an emission line object from that expected (in the astrometric solution) for a power-law source. Peters et al. (2015) have developed a formalism for including this information with color information, but more work is needed to fully leverage this resource.

Selection by Variability

In many ways variability will be the cornerstone of object classification for LSST. However, variability by itself is unlikely to be a panacea. Even for luminous quasars, it has been shown that variablity combined with colors works better for selection than variability alone (Peters et al. 2015).

Moreover, for low-luminosity AGNs which are expected to have the most variable nuclei, increasing contamination from the host galaxy will compromise variability-selection methods if insufficient care is taken. Thus one clear to do item for variability selection is to team up with other groups with more expertise in difference imaging in order to isolate the variability properties of the *nuclear* emission.

The next most crucial step for variability analysis may well be determining how to make use of *all* of the data. Specifically, most current investigations looking at variability only use one photometric bandpass, whereas LSST will have 6. For the *gri* data, it may be sufficient to apply a median-color based offset and treat the (non-simultaneous) data as one (e.g., by kriging the data together) with better time resolution than would be available with just a single band. The fact that quasars are systematically bluer when brighter will add a complication to such efforts, however. For the z and y data, low S/N may make it difficult to treat these measurements equivalently to *gri*.

Moreover, the spatial (and thus time) separation of g and y could actually degrade the accuracy of a merged light curve. For the u-band data, low S/N and sampling of the Ly-α forest rather than the quasar continuum at high-redshift will add complications. These are issues that can be further investigated with existing (and ongoing) data sets such as Stripe 82, DES, and Pan-STARRS.

Lastly, unlike magnitudes which are uniformly measured for all objects, light curves are difficult to analyze in a non-parametric fashion. A functional form (or forms) must be agreed upon and it must be realized that without an accurate redshift, comparison of variability parameters often compares very different rest frames. A-γ is certainly the simplest parameterization, but the damped random walk (DRW) is currently the most popular. Further work is needed to determine if these are sufficiently accurate to use or if a different parameterization might be more effective.

Work with SDSS Stripe 82 has allowed some early work in this direction. More still needed, possibly taking advantage also of Kepler, SDSS-RM, and/or OzDES data.

Combination with Multiwavelength Data

The last way that LSST will identify BHs is by combining with multiwavelength data. This can be considered more generally as "combination with data from other facilities" as some data (e.g., Euclid) may also be in the optical.

We will largely concentrate on the tasks needed for obscured quasars and low-luminosity AGNs as multi-wavelength data will likely add only episilon to our efforts robust selection of luminous type 1 quasars. This is particularly true at high reshift since combining with multiwavelength data generally means focusing on the brightest objects given how much deeper (for a given SED) LSST will reach than the typical IR and X-ray limits of large-area surveys. In nearly all cases we will have tiered multiwavelength data to contend with: shallow over a large area to deep over a small area.

For unobscured AGNs multiwavelength data can be used to modify the AGN probabilities for objects on the border; this will be most useful within the context of a probabilistic redshift distribution (see next subsection). Objects detected in the X-ray or IR with sufficiently high predicted luminosity will have increased AGN probability. Objects detected in the UV will have significantly decreased AGN probability.

For obscured and low-luminosity AGNs, the optical data from LSST may not be sufficient to identify the object as an AGN. Some low-luminosity AGNs may be identified as having nuclear variability, but for the faintest objects the errors on the variability will be insufficient for robust classification. As such, for these classes of objects will we be completely dependent upon multi-wavelenth SED fitting and X-ray and/or IR luminosity and radio morphology to identify as AGNs what LSST sees as a galaxy.

Crucial for these endeavors will be the Deep Drilling Fields (DDFs). Here is where there exists the most multiwavelength coverage. The DDFs will serve as a testbed for multiwavelength analysis in larger areas (by allowing us to understand what the brightest objects will look like). They will also provide the greatest depth (for a given completeness and efficiency) for AGN selection. Moreover they will have (outside of Stripe 82) the greatest density of spectral coverage and will essentially *define* the completeness and efficiency of AGN selection for the full survey area by providing small-area "truth tables". Such work will be crucial for the science efforts discussed below but also for early "reverberation mapping" work.

One of the biggest challenges will be conducting a sort of VO-like cataloging of the multiwavelength imaging data that will be used for these efforts. There may be no practical way to include *all* of the multiwavelength data and that task may fall on individual PIs of those programs. However, LSST should, at the very least identify key deep and wide data sets that should be matched in the course of pre-planned LSST analysis. Currently the greatest depth of the full sky is 2MASS in the near-IR, *WISE* in the mid-IR, *ROSAT* in the X-ray, and NVSS in the radio (soon to be replaced by EMU/Wodan). Somewhat deeper, but with less coverage we have UKIDSS and VHS in the near-IR; SpIES, SSDF, SERVS, SDWFS, and SWIRE in the mid-IR; the XMM Slew Survey and ChAMP in the X-ray; and GALEX in the UV. The key deep fields will be located within the DDFs. [GTR: Add any crucial missing data sets.]

It is with the multiwavelength data that true bandmerging will be required. That is the nearest positional match in another wavelength may not be the correct match to the LSST source. We must perform an astrophysically based SED matching using a suite of templates to determine the best matches. Such efforts have already received attention in the literature (e.g., Budavari & Szalay 2008) and preliminary work can proceed in earnest in the coming years.

Photometric Redshifts

Photo-z methods for AGNs can generally be broken into two methodologies: template-fitting (e.g., Salvato) and empirical (e.g., Richards et al. 2001). Template fitting is the method of choice for objects that exhibit a spectral break that can be used to broadly (perhaps even narrowly) isolate the redshift. A number of algorithms are in existence: EAZY, LePhare, ZEBRA, to name a few. Arguably more important that the algorithm is the suite of templates used. There is no lack of data to test these algorithms and work to chose an optimal algorithm and templates can and should proceed in the next few years. Indeed, this may not be a separate task from the broader galaxy photo-z efforts.

However, it is known that template fitting algorithms break down for luminous quasars as such objects exhibit no strong spectral break in the LSST filters (with the exception of high-redshift quasars where template fitting can still be effective); see Assef et al. 2010. In these cases empirical methods will be more effective. Thus one of the short-term tasks for LSST should be an attempt to merge these algorithms or learn how to smoothly morph between them as a function of luminosity should it be found that a single algorithm (and set of templates) is not sufficient.

Regardless of the algorithm LSST astronomers will need to become comfortable with working with photo-z probability distribution functions (PDFs). That is photo-z's will not consist of single predicted redshifts with errors, but rather will be a vector of probabilities at *every* redshift. Di Pompeo et al. 2015 provides an example of analysis performed with photo-z PDFs.

Expected Number of AGNs

Currently the prediction for the number of AGNs that LSST will observe is largely based on Hopkins, Richards, & Hernquist (2007). That work combined all of the best multiwavelength quasar luminosity functions (across all redshifts) that were available in 2007 and provided code to determine the expected number of *all* AGNs at any redshift and luminosity. However, since that time new work has revealed significant changes in the best-fit luminosity function. The most obvious is the slope of the bright-end of the QLF at high redshift, which for many years has been thought to be quite flat. Jiang et al. 20??, McGreer et al. 2013, and Ross et al. 2013 have subsequently shown that what we thought was the bright end of the QLF at high-z was really the faint end and that the break luminosity is much brighter than expected. Graphically this can be understood as Figure 10.8 in the LSST Science Book as showing a high-z decline of Lstar (the solid black line) that is too steep. Practically this means that the number of high-redshift AGNs will change. Further changes may come from modification of the type 2 to type 1 ratio as a function of luminosity.

What is needed here is for someone to take on the (relatively) thankless task of updating HRH07. As encouragement, the 500+ citations for HRH07 may mean that this task won't be quite so thankless!

4.1.2 Luminosity Function

Despite countless dedicated efforts, it remains true that our understanding of the luminosity function of AGNs is incomplete and a much-improved LF will be a major result from LSST. Updating HRH07 as noted above is one task that is needed here in the short-term. Largely this is to ensure that the LF that serves as an *input* to LSST simulations is as accurate as possible.

We emphasize that this task is absolutely *not* something that needs to wait for data. LSST should endeavor to publish a LF paper *before* any data are taken—using the simulated data. Such a paper will serve as a template for data-based analysis in the future, but more importantly will serve as a guide for the expected errors as a function of redshift and magnitude. Differences between the predicted and observed LFs will guide understanding of differences in BH physics from the predicted model.

Such work will also serve as a guideline for how LSST will determine the completeness, efficiency and total volume searched for a necessarily probabilistic sample. As already discussed above, precursor spectroscopy, especially in the DDFs and/or Stripe 82 will be needed to serve as truth tables in this analysis.

4.1.3 Clustering

Some of the greatest gains on BH physics will come from an array of clustering analyses that LSST will uniquely be able to perform. In large part this comes about because high densities and accurate redshifts are needed to robust clustering analysis. Currently high densities are not being achieved over sufficient area at high redshift (and interesting depth) and photometric redshift accuracy (largely due to catastrophic errors) is a limiting factor at lower redshifts.

Most needed here is preliminary work in Stripe 82 where the depth (both in the mid-IR and optical), areal coverage, and existing spectral density provide an excellent testbed. Stripe 82 also serves as an excellent testbed for photometric redshift testing.

As with the LF, a series of preliminary clustering papers can be produced in advance of LSST by taking advantage of simulated data. Particularly interesting will clustering of faint sources at high-redshift, clustering of obscured vs. unobscured AGN, and clustering of hard- vs. soft-spectrum AGNs. The latter is of interest as even bona-fide quasars are expected to exhibit a large range of masses and accretion rates.

4.1.4 Multiwavelength Physics

Much of the work needed here has already been discussed above. The most challenging will be the fact that some AGNs will be invisible in the optical alone but will be discoverable through combination with multi-wavelength data. LSST needs to develop formalism for doing this.

4.1.5 Variability

Again, much of the work needed here has been described above. However, we emphasize that variability analysis for AGN *selection* will necessarily be different from variability analysis for AGN *physics*. The obvious different being the need to work in the rest frame vs. the observed frame. Thus photometric redshifts will play a key role. Similarly, work needs to be done to determine if the variabiltiy parameterization for selection and physics should be the same or different.

Early work can be done with simulated data on nearly all of the areas of variability science, including characterization of AGN variability, power density spectra, photometric reverberation mapping, accretion disk sizes, and lensing time delays.

4.1.6 Transient Fueling Events

The above text has largely concentrated on identification of relatively long-lived BH fueling events. Someone should fill in to do items for identification of transient fueling events and for doing BH physics with such events.

4.1.7 Gravitational Lenses

The strong lens working group will have their own road map task list, but beyond robust AGN identification and photometric redshift estimation, gravitational lensing work will also be concerned with morphology, deblending, and lensing galaxy identification.

4.1.8 Miscellaneous

Other to do items not covered above include the need to build a database of existing spectroscopic identifications, obtaining additional spectroscopy in the DDFs and Stripe 82, pre-planning for follow-up observations, and announcing LSST observing schedule to other facilities.

4.2 Galaxy Evolution Task Lists

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

The task list presented here highlights the preparation work needed in the next 3-4 years. Of primary importance are tasks that might influence the detailed survey design or the algorithms used in the DM to construct catalogs. These are the most urgent. Also included are activities that can be reasonably independent of the LSST survey design and DM optimization, but which will ensure good support for LSST galaxy studies.

4.2.1 Techniques, Algorithms, or Software Development

T-1. Techniques for finding low-surface-brightness features or galaxies

Motivation: A huge benefit of LSST relative to prior large-area surveys will be its ability to detect low-surface-brightness (LSB) features associated with galaxies. This includes tidal streams and other features associated with past and ongoing mergers, it includes intra-cluster and intra-group light, and it includes relatively nearby, extended low-surface-brightness galaxies. Prior to LSST, typical studies of the low-surface-brightness universe have focused on relatively small samples, often selected by criteria that are difficult to quantify or reproduce in theoretical models. Measurements of the LSB features themselves themselves are challenging, often requiring hand-tuning and interactive scientific judgment. This is important for accurately quantifying what we observe, but such interactive tuning of the measurements (a) is not something that can be applied on the LSST scale and (b) is difficult to apply to theoretical models. For LSST it is crucial that we automate the detection and characterization of LSB 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 crucial importance: (1) simulating realistic LSB features, (2) using the simulations to optimize detection and measurement, (3) ensuring that LSST level-2 processing strategies and observing strategies are at least cognizant of 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.

It is important to insert realistic low-surface-brightness features into LSST simulated images and try to extract and measure them, exploring different techniques or algorithms for doing the detection and measurement. Because the LSB objects are sparse on the sky, making realistic LSST sky images is probably not the most efficient way to accomplish this; more targeted simulations with a higher density of LSB objects are needed. The simulated observations need to be realistic in their treatment of scattered light, particularly scattering from bright stars which may or may not be in the actual field of view of the telescope. Scattering from bright stars is likely to be the primary source of contamination when searching for extended LSB features. Ideally, the LSST scattered-light model, tuned by repeated observations, will be sufficiently good that these contaminants can be removed or at least flagged at level 2. Defining the metrics for "sufficiently good," based on analysis of simulations, is 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 it is unclear yet whether the science benefit can justify the extra effort.

Because the LSST source extraction is primarily optimized for finding faint, barely-resolved galaxies, it is going to be challenging to optimize simultaneously for finding large LSB structures and cataloging them as one entity in the database. For very large structures, analysis of the LSST "sky background" map, might be the most productive approach. We need to work with the LSST project to make sure the background map is stored 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 from 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, it is likely that the database will contain pieces of the structure, either as portions of a hierachical family of deblended objects, or cataloged as separate objects. 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 collaboration might be an extra set of fields for the database to indicate which separate objects are probably part of the same physical entity. This would be sparsely populated in the first year or two of LSST, but by the end of the survey could be a useful resource for a wide variety of investigations.

Deliverables: Deliverables over the next several years from the activities described above include the following:

a) realistic inputs of LSB galaxies or LSB features for the LSST image simulations;

b) custom simulations;

c) algorithms for finding and measuring LSB features;

d) input to the Project on scattered-light mitigation and modeling strategies;

e) input to the project on photometric and morphological parameters to measure/store at level 2;

f) query strategies and sample queries for finding LSB structures; and

g) a baseline concept for a value-added database of LSB structures

T-2. Techniques for identifying and deblending overlapping galaxies

Motivation: The Level 2 data products are the most relevant starting point for galaxy-evolution science. In the LSST nomenclature, `Objects` represent astrophysical entities (stars, galaxies, quasars, etc.), while `Sources` represent their single-epoch observations. The master list of Objects in Level 2 will be generated by associating and deblending the list of single-epoch source detections and the lists of sources detected on coadds. The exact strategies for doing this are still under active development by the LSST project, and engagement with the science community is essential. While each data release will have unique object IDs, it will be a huge impediment for LSST science if the first few generations of catalogs turn out severely the limit the science that can be done via database queries.

For galaxies science, the issue of deblending is of 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 the object in question is a single object at one redshift, not 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) have reasonably clean catalogs to start with and (b) be able to model the effects of blending on the sample selection and derivation of redshift and other parameters. This is critical not just for galaxy-evolution science, but for lensing and large-scale structure studies. This is just one example. Another is the evolution of galaxy morphologies, where the effects of blending and confusion may well be the dominant source of uncertainty.

The plan for the level-2 catalogs is that sources are hierarchically deblended and that this hierarchy is maintained in the catalog. Scientifically important decisions are still to be made about whether and how to use color information in the deblending, and how to divide the flux between overlapping components. Even if the Project is doing the development work, engagement with the community is important for developing 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 have realistic source densities, redshift distributions, sizes, and color distributions. However, the input galaxies do not have realistic morphologies. At least some simulations with realistic morphologies are needed, especially for the Deep Drilling Fields. Inputs should come both from hydrodynamical simulations (where "truth" is known), *Hubble* images, and images from precursor surveys such as CFHTLS, DES and HyperSuprimeCam. The science collaborations should help provide and vet inputs.

More challenging is to come up with 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 have been made over the past few years to incorporate color information into the deblending algorithm, but this needs much more attention, not only for developing and testing algorithms, but for deciding on figures-of-merit for their performance.

Deliverables: Deliverables over the next several years from the activities described above include the following:

a) providing realistic galaxy image inputs to the ImSim team;

b) developing tests and figures of merit to quantify the effects on several science objectives;

c) assessing the current baseline plan for level-2 deblending and for parameter estimation for blended objects; and

d) developing prototype implementations of deblending algorithms that take advantage of the LSST color information.

T-3. Optimizing Galaxy Morphology Measurements

Motivation: Measurements of galaxy morphologies are an important tool for constraining models of galaxy evolution. While fairly simple measures of galaxy ellipticity and position angles may be sufficient for the Dark Energy science goals, other kinds of measurements are needed for galaxy-evolution science. The "multifit" approach of fitting simple parametric models to galaxy profiles has been the baseline plan. This will be useful but insufficient. For well-resolved galaxies it is desirable to have separate measures of bulge and disk, and spiral-arm structure, measures of concentration, asymmetry, and clumpiness. These 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 there will no doubt be optimization in level 3 processing, it is important to have enough information in the level 2 output products to pick reasonable subsets of galaxies.

Activities: The preparation work, therefore, focuses on defining measures to enable these queries. 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 measure of morphology (e.g. the CAS, GINI and M20 parameters), develop new LSST-optimized parameters, and optimize their computation to avoid taxing the level-2 pipeline.

Given the very large data set and the uncertainty in how to use specific morphological parameters to choose galaxies in certain physical classes (e.g. different merger stages or stages of disk growth), it is important to have extensive training both from hydrodynamical simulations with dust (where physical truth is known, even if the models are imperfect) and from observations where kinematics or other information provide a good understanding of the physical nature of the object. These training sets ought to be classified by humans (still the gold-standard for image classification) and via machine-learning techniques applied to the morphological measurements. A series of "classification challenges" prior to the LSST survey could help to refine the techniques.

Deliverables: Deliverables over the next several years from the activities described above include the following:

a) providing realistic galaxy image inputs for classification tests to the ImSim team;

b) human classification of the images;

c) machine-learning algorithms to be tested and developed into suitable SQL queries;

d) developing a menu of candidate morphological measurements for level 2 and level 3 processing; and

e) developing tests and figures of merit to quantify the effects on several science objectives.

T-4. Optimizing Galaxy Photometry

Motivation: Systematic uncertainties will dominate over random uncertainties for almost any research question one can imagine addressing with LSST. The most basic measurement of a galaxy is its flux in each band, but this is a remarkably subtle measurement for a variety of reasons: 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 thrown off 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: Deliverables over the next several years from the activities described above include the following:

a) developing metrics for various science cases to help evaluate the level 2 photometry;

b) providing 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 develping optimal techniques for forced photometry using priors from the space missions.

T-5. Optimizing Measurements of Stellar Population Parameters

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 star-formation histories for a single galaxy based on only the LSST bands will be highly uncertain, due 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 it does 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.
Another important activity is to identify the ancillary data sets and observing opportunities, especially for the deep fields.

Deliverables: Deliverables over the next several years from the activities described above include the following:

a) developing and refining techniques for constraining star-formation histories of large ensembles of galaxies;

b) providing model inputs to guide in developing these techniques;

c) refining the science requirements for ancillary multi-wavelength data to support LSST.

T-6. Software Integration

Motivation: The LSST Project is responsible for level 2 data processing, and the community is expected to any processing beyond that as level 3. Furthermore, some algorithms developed as part of the level 3 effort are expected to migrate to level 2. There needs to be strong coordination between the Project and the community for this concept to work. This includes training in developing level 3 software and community engagement in defining the requirements and interfaces.

Activities: The most urgent activity is to develop some early prototypes of level 3 software so that the interfaces can be worked out on realistic use cases.

Deliverables:

4.2.2 Precursor Observations or Synergy with Other Facilities

T-1. Redshift surveys in the Deep Drilling fields

Motivation:

Activities:

Deliverables:

T-2. Ancillary Data in Deep Drilling fields

Motivation:

Activities:

Deliverables:

T-3. Photometric redshift training and calibration

Motivation:

Activities:

Deliverables:

T-4. Joint use of spectroscopic and photometric redshifts

Motivation:

Activities:

Deliverables:

4.2.3 LSST-targeted theory or simulations

T-1. Image simulations of galaxies with complex morphologies

Motivation:

Activities:

Deliverables:

T-2. Rare objects

Motivation:

Activities:

Deliverables:

T-3. Cosmic Variance estimators

Motivation:

Activities:

Deliverables:

T-4. Nearby dwarfs: surface brightness fluctuations

Motivation:

Activities:

Deliverables:

T-5. Testing group and void finders

Motivation:

Activities:

Deliverables:

4.2.4 Databases and Data Services

T-1. Data structures to characterize survey biases and completeness

Motivation:

Activities:

Deliverables:

T-2. Queries to find unusual class of objects

Motivation:

Activities:

Deliverables:

T-3. Compact representations of likelihood functions

Motivation:

Activities:

4.3 Astroinformatics Task Lists

4.4 Large Scale Structure Task Lists

4.5 Strong Lensing Task Lists

4.6 Weak Lensing Task Lists

References

Abell, P. A. et al., 2009, 0912.0201
Abraham, R. G., van den Bergh, S., & Nair, P., 2003, *ApJ*, 588, 218
Abraham, R. G., & van Dokkum, P. G., 2014, *PASP*, 126, 55
Bullock, J. S., & Johnston, K. V., 2005, *ApJ*, 635, 931
Conselice, C. J., Bershady, M. A., Dickinson, M., & Papovich, C., 2003, *AJ*, 126, 1183
Flaugher, B., 2005, International Journal of Modern Physics A, 20, 3121
Grogin, N. A. et al., 2011, *ApJS*, 197, 35
Heckman, T. M. et al., 2005, *ApJL*, 619, L35
Johnston, K. V., Bullock, J. S., Sharma, S., Font, A., Robertson, B. E., & Leitner, S. N., 2008, *ApJ*, 689, 936
Kaiser, N. et al., 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7733, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, p. 0
Kartaltepe, J. S. et al., 2007, *ApJS*, 172, 320
Koekemoer, A. M. et al., 2011, *ApJS*, 197, 36
Lin, L. et al., 2008, *ApJ*, 681, 232
Lotz, J. M. et al., 2008, *ApJ*, 672, 177
Lotz, J. M., Primack, J., & Madau, P., 2004, *AJ*, 128, 163
Madau, P., & Dickinson, M., 2014, *ARAA*, 52, 415
Martínez-Delgado, D., Peñarrubia, J., Gabany, R. J., Trujillo, I., Majewski, S. R., & Pohlen, M., 2008, *ApJ*, 689, 184
Miyazaki, S. et al., 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 8446, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, p. 0
Noeske, K. G. et al., 2007, *ApJL*, 660, L43
Robotham, A. S. G. et al., 2014, *MNRAS*, 444, 3986
van Dokkum, P. G., Abraham, R., & Merritt, A., 2014, *ApJL*, 782, L24
York, D. G. et al., 2000, *AJ*, 120, 1579