

# 1 Introduction

*Anthony Tyson, Michael A. Strauss, Željko Ivezić*

Wide-angle surveys have been an engine for new discoveries throughout the modern history of astronomy, and have been among the most highly cited and scientifically productive observing facilities in recent years. Over the past decade, large scale sky surveys in many wavebands, such as the Sloan Digital Sky Survey (SDSS), Two-Micron All Sky Survey (2MASS), Galaxy Evolution Explorer (GALEX), Faint Images of the Radio Sky at Twenty-centimeters (FIRST), and many others have proven the power of large data sets for answering fundamental astrophysical questions. This observational progress, based on advances in telescope construction, detectors, and above all, information technology, has had a dramatic impact on nearly all fields of astronomy and many areas of fundamental physics. The hardware and computational technical challenges and the exciting science opportunities are attracting scientists from high-energy physics, statistics, and computer science. These surveys are most productive and have the greatest impact when the data from the surveys are made public in a timely manner. The LSST builds on the experience of these surveys and addresses the broad scientific goals of the coming decade.

## 1.1 Astronomy-Physics Interaction

The astronomical discovery that ordinary matter, i.e., that made of familiar atoms, comprises only 4% of the mass-energy density of the Universe is the most dramatic in cosmology in the past several decades, and it is clear that new physics will be needed to explain the non-baryonic dark matter and dark energy. At the same time, data from particle physics suggests a corresponding need for physics beyond the Standard Model. Discovering and understanding the fundamental constituents and interactions of the Universe is the common subject of particle physics and cosmology. In recent years, the frontier questions in both fields have become increasingly intertwined; in addition to the dark matter and dark energy questions, astronomical observations have provided the best evidence to date for non-zero neutrino masses, have suggested phase transitions leading to inflation in the early Universe, give the best constraints on alternative theories of gravity on large scales, and allow us to test for time variations in the fundamental physical constants.

The emerging common themes that astrophysics and particle physics are addressing have crystallized a new physics-astronomy community. The number of particle physicists taking active roles in astrophysics has increased significantly. Understanding the origin of dark matter and dark energy will require simultaneous progress in both particle physics and cosmology, in both theory and experiment. Discoveries with LSST and the Large Hadron Collider will rely on scientists covering a broader intellectual frontier, and require enhanced collaboration between theorists and experimentalists in particle physics, cosmology, and astrophysics generally.

## 1.2 What a Telescope with Enormous Étendue can Accomplish

A survey that can cover the sky in optical bands over wide fields to faint magnitudes with a fast cadence is required in order to explore many of the exciting science opportunities of the next decade. The most important characteristic that determines the speed at which a system can survey the sky to a given depth is its étendue (or grasp): the product of its primary mirror area (in square meters) and the area of its field-of-view (in square degrees). Imaging data from a large ground-based active optics telescope with sufficient étendue can address many scientific missions simultaneously rather than sequentially. By providing unprecedented sky coverage, cadence, and depth, the LSST makes it possible to attack multiple high-priority scientific questions that are far beyond the reach of any existing facility.

The effective étendue for LSST will be  $319 \text{ m}^2\text{deg}^2$ , more than an order of magnitude larger than that of any existing facility. Full simulations of LSST's capabilities have been carried out, as described below. The range of scientific investigations that will be enabled by such a dramatic improvement in survey capability is extremely broad. These new investigations will rely on the statistical precision obtainable with billions of objects. Thus hundreds of deep exposures are required in each band to gain control of low-level systematics. Hundreds of deep and short exposures are also required in order to fully explore the faint time domain on short timescales. This wide-fast-deep requirement led to the LSST design. The history of astronomy has taught us that there are unanticipated surprises whenever we view the sky in a new way. The wide-fast-deep survey capability of LSST promises significant advances in virtually all areas of astrophysics.

## 1.3 The History of the Idea

The value of wide area imaging of the sky has long been recognized: motivated by the opportunities of statistical astronomy, telescope and detector research and development (R&D) campaigns in the 1930s and 1940s at Caltech and Kodak gave rise to the Palomar Observatory Sky Survey (POSS, 1948-1957). While POSS enabled significant advances in astronomy through follow-up observations, the next revolution – very deep imaging – had to wait 25 years for digital data from a new detector technology. Early Charge-Coupled Devices (CCDs) were ten thousand times smaller in area than the POSS plates, but the promise of high quantum efficiency for astronomical applications (including the Hubble Space Telescope (HST)) kept R&D on scientific grade CCDs alive in the 1970s and 1980s. With their higher sensitivity and linearity, these early CCDs led to many astronomical advances. Eventually larger scientific CCDs were developed, leading to focal plane mosaics of these CCDs in the early 1990s. The Big Throughput Camera (Wittman et al. 1998, BTC) on the 4-meter Blanco telescope enabled the surveys that discovered high-redshift supernovae and suggested the existence of dark energy. A mosaic of these same CCDs led to the Sloan Digital Sky Survey (York et al. 2000, SDSS), which has imaged over  $10,000 \text{ deg}^2$  of sky in five broad bands. SDSS has been hugely successful because the high étendue of the telescope/camera combination enabled a wide survey with well-calibrated digital data.

Wide surveys are very productive; the SDSS, for example, was cited as the most productive telescope in recent years (Madrid & Macchetto 2009). The discovery space could be made even larger if the survey could be made deep and with good time resolution (fast). LSST had its origin in the

realization in the late 1990s – extrapolating from the BTC on the 4-meter telescope – that a wide-fast-deep optical sky survey would be possible if the size and field of view of the camera+telescope were scaled up. The challenge was to design a very wide field telescope with state-of-the-art image quality. Originally, 4-meter designs with several square degrees field of view were studied. However, it was soon realized that larger étendue and better image performance than realizable in two-mirror+corrector designs would be required to address a broad range of science opportunities simultaneously with the same data. Indeed the three-mirror modified Paul-Baker design suggested by Roger Angel in 1998 for the “Dark Matter Telescope” (DMT) had its origin in two very different wide-fast-deep survey needs: mapping dark matter via weak gravitational lensing and detecting faint Solar System bodies (Angel et al. 2000; Tyson et al. 2001).

Plans for the “6-meter class” DMT wide field telescope and camera were presented at a workshop on gravity at SLAC National Accelerator Laboratory in August 1998 (Tyson 1998). The science case for such a telescope was submitted to the 2000 Astronomy and Astrophysics Decadal Survey in June 1999. That National Research Council (NRC) report recommended it highly as a facility to discover near-Earth asteroids as well as to study dark matter, and renamed it the Large Synoptic Survey Telescope (LSST). In order to explore the science opportunities and related instrument requirements, a Science Drivers Workshop was held at the National Optical Astronomy Observatory (NOAO) in November 2000. A summer workshop on wide field astronomy was held at the Aspen Center for Physics in July 2001, arguably the beginning of wide involvement by the scientific community in this project. Many alternative system designs were studied, but the need for short, deep, and well sampled wide-field exposures led naturally to a single large telescope and camera. At the behest of the National Science Foundation (NSF) astronomy division, NOAO set up a national committee in September 2002, with Michael Strauss as chair, to develop the LSST design reference mission (Strauss et al. 2004). Plans for a Gigapixel focal plane (Starr et al. 2002), as well as initial designs for the telescope-camera-data system (Tyson 2002), were presented in 2002. In 2002 the NSF funded development of the new imagers required for LSST, supplementing an investment already made by Bell Labs. Lynn Seppala modified Roger Angel’s original three-mirror optical design (Angel et al. 2000), creating a wider, very low distortion field. Also in 2002 the LSST Corporation was formed to manage the project. A construction proposal was submitted to the NSF in early 2007 and favorably reviewed later that year. In 2008 the LSST 8.4-m primary-tertiary mirror (§ 2.3) was cast, and in early 2009 the secondary mirror blank was cast as well.

## 1.4 Overview of LSST Science

Guided by community-wide input, the LSST is designed to achieve multiple goals in four main science themes: Taking an Inventory of the Solar System, Mapping the Milky Way, Exploring the Transient Optical Sky, and Probing Dark Energy and Dark Matter. These are just four of the many areas on which LSST will have enormous impact, but they span the space of technical challenges in the design of the system and the survey and have been used to focus the science requirements.

The LSST survey data will be public with no proprietary period in the United States, with a goal to make it world-public. As was the case with SDSS, we expect the scientific community will produce a rich harvest of discoveries. Through the science collaborations, the astronomical and physics communities are already involved in the scientific planning for this telescope.

Each patch of sky will be visited 1000 times (where a *visit* consists of two 15-second exposures back to back in a given filter) in ten years, producing a trillion line database with temporal astrometric and photometric data on 20 billion objects. The 30 terabytes of pipeline processed data (32 bit) obtained each night will open the time domain window on the deep optical universe for variability and motion. Rarely observed events will become commonplace, new and unanticipated phenomena will be discovered, and the combination of LSST with contemporary space-based near-infrared (NIR) missions will provide powerful synergies in studies of dark energy, galaxy evolution, and many other areas. The deep coverage of ten billion galaxies provides unique capabilities for cosmology. Astrometry, six-band photometry, and time domain data on 10 billion stars will enable studies of Galactic structure. All LSST data and source code will be non-proprietary, with public accessibility and usability a high priority. A goal is to have worldwide participation in all data products.

This book describes in detail many of the scientific opportunities that LSST will enable. Here we outline some of the themes developed in the chapters that follow:

- **A Comprehensive Survey of the Solar System (Chapter 5):**

The small bodies of the Solar System offer a unique insight into its early stages. Their orbital elements, sizes, and color distributions encode the history of accretion, collisional grinding, and perturbations by existing and vanished giant planets. Farther out, runaway growth never occurred, and the Kuiper belt region still contains a portion of the early planet population. Understanding these distributions is a key element in testing various theories for the formation and evolution of our planetary system. LSST, with its unprecedented power for discovering moving objects, will make major advances in Solar System studies. The baseline LSST cadence will result in orbital parameters for several million moving objects; these will be dominated by main belt asteroids (MBAs), with light curves and colorimetry for a substantial fraction of detected objects. This represents an increase of factors of ten to one hundred over the numbers of objects with documented orbits, colors, and variability information.

Our current understanding of objects beyond Neptune (trans-Neptunian Objects, or TNOs) is limited by small sample sizes. Fewer than half of the  $\sim 1000$  TNOs discovered to date are drawn from surveys whose discovery biases can be quantified, and only several hundred TNOs have measured colors. The LSST will survey over half the celestial sphere for asteroids, get superb orbits, go tremendously faint, and measure precise colors, allowing measurement of light curves for thousands of TNOs, producing rotation periods and phase curves, yielding shape and spin properties, and providing clues to the early environment in the outer Solar System. Moreover, these objects fall into a wide variety of dynamical classes, which encode clues to the formation of the Solar System.

Many asteroids travel in Earth-crossing orbits, and Congress has mandated that National Aeronautics and Space Administration (NASA) catalog 90% of all potentially hazardous asteroids larger than 140 meters in diameter. The LSST is the only ground-based survey that is capable of achieving this goal (Ivezić et al. 2008).

- **Structure and Stellar Content of the Milky Way (Chapters 6 and 7):**

Encoded in the structure, chemical composition and kinematics of stars in our Milky Way is a history of its formation. Surveys such as 2MASS and SDSS have demonstrated that the

halo has grown by accretion and cannibalization of companion galaxies, and it is clear that the next steps require deep wide-field photometry, parallax, proper motions, and spectra to put together the story of how our Galaxy formed. LSST will enable studies of the distribution of numerous main sequence stars beyond the presumed edge of the Galaxy's halo, their metallicity distribution throughout most of the halo, and their kinematics beyond the thick disk/halo boundary, and will obtain direct distance measurements below the hydrogen-burning limit for a representative thin-disk sample. LSST is ideally suited to answering two basic questions about the Milky Way Galaxy: What is the structure and accretion history of the Milky Way? What are the fundamental properties of all the stars within 300 pc of the Sun?

LSST will produce a massive and exquisitely accurate photometric and astrometric data set. Compared to SDSS, the best currently available optical survey, LSST will cover an area more than twice as large, using hundreds of observations of the same region in a given filter instead of one or two, and each observation will be about two magnitudes deeper. LSST will detect of the order  $10^{10}$  stars, with sufficient signal-to-noise ratio to enable accurate light curves, geometric parallax, and proper motion measurements for about a billion stars. Accurate multi-color photometry can be used for source classification (1% colors are good enough to separate main sequence and giant stars, [Helmi et al. 2003](#)), and measurement of detailed stellar properties such as effective temperatures to an rms accuracy of 100 K and metallicity to 0.3 dex rms.

To study the metallicity distribution of stars in the Sgr tidal stream ([Majewski et al. 2003](#)) and other halo substructures at distances beyond the presumed boundary between the inner and outer halo ( $\sim 30$  kpc, [Carollo et al. 2007](#)), the coadded depth in the  $u$  band must reach  $\sim 24.5$ . To detect RR Lyrae stars beyond the Galaxy's tidal radius at  $\sim 300$  kpc, the single-visit depth must be  $r \sim 24.5$ . In order to measure the tangential velocity of stars to an accuracy of  $10 \text{ kms}^{-1}$  at a distance of 10 kpc, where the halo dominates over the disk, proper motions must be measured to an accuracy of at least  $0.2 \text{ mas yr}^{-1}$ . The same accuracy follows from the requirement to obtain the same proper motion accuracy as Gaia ([Perryman et al. 2001](#)) at its faint limit ( $r \sim 20$ ). In order to produce a complete sample of solar neighborhood stars out to a distance of 300 pc (the thin disk scale height), with  $3\sigma$  or better geometric distances, trigonometric parallax measurements accurate to 1 mas are required. To achieve the required proper motion and parallax accuracy with an assumed astrometric accuracy of 10 mas per observation per coordinate, approximately 1,000 observations are required. This requirement on the number of observations is close to the independent constraint implied by the difference between the total depth and the single visit depth.

- **The Variable Universe (Chapter 8):**

Characterization of the variable optical sky is one of the true observational frontiers in astrophysics. No optical telescope to date has had the capability to search for transient phenomena at faint levels over enough of the sky to fully characterize the phenomena. Variable and transient phenomena have historically led to fundamental insights into subjects ranging from the structure of stars to the most energetic explosions in the Universe to cosmology. Existing surveys leave large amounts of discovery parameter space (in waveband, depth, and cadence) as yet unexplored, and LSST is designed to start filling these gaps.

LSST will survey the sky on time scales from years down to 15 seconds. Because LSST extends

time-volume space a thousand times over current surveys, the most interesting science may well be the discovery of new phenomena. With its repeated, wide-area coverage to deep limiting magnitudes, LSST will enable the discovery and analysis of rare and exotic objects, such as neutron star and black hole binaries and high-energy transients, such as optical counterparts to gamma-ray bursts and X-ray flashes (at least some of which apparently mark the deaths of massive stars). LSST will also characterize in detail active galactic nuclei (AGN) variability and new classes of transients, such as binary mergers and stellar disruptions by black holes. Perhaps even more interesting are explosive events of types yet to be discovered, such as predicted mergers among neutron stars and black holes. These may have little or no high-energy emission, and hence may be discoverable only at longer wavelengths or in coincidence with gravitational wave events.

LSST will also provide a powerful new capability for monitoring periodic variables such as RR Lyrae stars, which will be used to map the Galactic halo and intergalactic space to distances exceeding 400 kpc. The search for transients in the nearby Universe (within 200 Mpc) is interesting and urgent for two reasons. First, there exists a large gap in the luminosity of the brightest novae ( $-10$  mag) and that of sub-luminous supernovae ( $-16$  mag). However, theory and reasonable speculation point to several potential classes of objects in this “gap”. Such objects are best found in the Local Universe. Next, the nascent field of gravitational wave astronomy and the budding fields of ultra-high energy cosmic rays, TeV photons, and astrophysical neutrinos are likewise limited to the Local Universe due to physical effects (GZK effect, photon pair production) or instrumental sensitivity (neutrinos and gravitational waves). Unfortunately, the localization of these new telescopes is poor, precluding identification of the host galaxy (with corresponding loss of distance information and physical diagnostics). Both goals can be met with a fast wide field optical imaging survey in concert with follow-up telescopes.

- **The Evolution of Galaxies (Chapters 9 and 10):**

Surveys carried out with the current generation of ten-meter-class telescopes in synergy with deep X-ray (Chandra X-ray Observatory, X-ray Multi-mirror Mission) and infrared (Spitzer Space Telescope) imaging have resulted in the outline of a picture of how galaxies evolve from redshift 7 to the present. We now have a rough estimate, for example, of the star formation history of the Universe, and we are starting to develop a picture of how the growth of supermassive black holes is coupled to, and influences, the growth of galaxy bulges. But the development of galaxy morphologies and the dependence on environment are poorly understood. In spite of the success of the concordance cosmological model and the hierarchical galaxy-formation paradigm, experts agree that our understanding of galaxy formation and evolution is incomplete. We do not understand how galaxies arrive at their present-day properties. We do not know if the various discrepancies between theory and observations represent fundamental flaws in our assumptions about dark matter, or problems in our understanding of feedback on the interstellar medium due to star formation or AGN activity. Because the process of galaxy formation is inherently stochastic, large statistical samples are important for making further progress.

The key questions in galaxy evolution over cosmic time require a deep wide-area survey to complement the more directed studies from HST, James Webb Space Telescope (JWST), and Atacama Large Millimeter Array (ALMA) and other narrow-field facilities. The essential

correlation of galaxy properties with dark matter — both on small scales in the local Universe and in gravitational lenses, and on the Gpc scales required for large-scale structure — requires a new generation wide-area survey. LSST promises to yield insights into these problems.

It is likely that AGN spend most of their lives in low-luminosity phases, outshone by their host galaxies, but recognizable by their variability. These will be revealed with great statistical accuracy by LSST in synergy with other facilities. The systematic evolution of AGN optical variability is virtually unexplored in large samples and would provide a new window into accretion physics.

- **Cosmological Models, and the Nature of Dark Energy and Dark Matter (Chapters 11-15):**

Surveys of the Cosmic Microwave Background (CMB), the large-scale distribution of galaxies, the redshift-distance relation for supernovae, and other probes, have led us to the fascinating situation of having a precise cosmological model for the geometry and expansion history of the Universe, whose principal components we simply do not understand. A major challenge for the next decade will be to gain a physical understanding of dark energy and dark matter. Doing this will require wide-field surveys of gravitational lensing, of the large-scale distribution of galaxies, and of supernovae, as well as next-generation surveys of the CMB (including polarization).

Using the CMB as normalization, the combination of these LSST deep probes over wide area will yield the needed precision to distinguish between models of dark energy, with cross checks to control systematic error. LSST is unique in that its deep, wide-field, multi-color imaging survey can undertake four cosmic probes of dark matter and dark energy physics with a single data set and with much greater precision than previously: 1) Weak lensing cosmic shear of galaxies as a function of redshift; 2) Baryon acoustic oscillations (BAO) in the power spectrum of the galaxy distribution; 3) Evolution of the mass function of clusters of galaxies, as measured via peaks in the weak lensing shear field; and 4) measurements of redshifts and distances of type Ia supernovae. The synergy between these probes breaks degeneracies and allows cosmological models to be consistently tested. By simultaneously measuring the redshift-distance relation and the growth of cosmic structure, LSST data can test whether the recent acceleration is due to dark energy or modified gravity. Because of its wide area coverage, LSST will be uniquely capable of constraining more general models of dark energy. LSST's redshift coverage will bracket the epoch at which dark energy began to dominate the cosmic expansion. Much of the power of the LSST will come from the fact that all the different measurements will be obtained from the same basic set of observations, using a facility that is optimized for this purpose. The wide-deep LSST survey will allow a unique probe of the isotropy and homogeneity of dark energy by mapping it over the sky, using weak lensing, supernovae and BAO, especially when normalized by Planck observations.

Gravitational lensing provides the cleanest and farthest-reaching probe of dark matter in the Universe, which can be combined with other observations to answer the most challenging and exciting questions that will drive the subject in the next decade: What is the distribution of mass on sub-galactic scales? How do galaxy disks form and bulges grow in dark matter halos? How accurate are CDM predictions of halo structure? Can we distinguish between a need for a new substance (dark matter) and a need for new gravitational physics? What is the dark matter made of anyway? LSST's wide-field, multi-filter, multi-epoch optical imaging survey

will probe the physics of dark matter halos, based on the (stackable) weak lensing signals from all halos, the strong lensing time domain effects due to some, and the distribution of 3 billion galaxies with photometric redshifts. LSST will provide a comprehensive map of dark matter over a cosmological volume.

## 1.5 The LSST Science Requirements

The superior survey capability enabled by LSST will open new windows on the Universe and new avenues of research. It is these scientific opportunities that have driven the survey and system design. These “Science Requirements” are made in the context of what we forecast for the scientific landscape in 2015, about the time the LSST survey is planned to get underway. Indeed, LSST represents such a large leap in throughput and survey capability that in these key areas the LSST remains uniquely capable of addressing these fundamental questions about our Universe. The long-lived data archives of the LSST will have the astrometric and photometric precision needed to support entirely new research directions which will inevitably develop during the next several decades.

We have developed a detailed LSST Science Requirements Document<sup>1</sup>, allowing the goals of all the science programs discussed above (and many more, of course) to be accomplished. The requirements are summarized as follows:

1. *The single visit depth* should reach  $r \sim 24.5$  ( $5\sigma$ , point source). This limit is primarily driven by need to image faint, fast-moving potentially hazardous asteroids, as well as variable and transient sources (e.g., supernovae, RR Lyrae stars, gamma-ray burst afterglows), and by proper motion and trigonometric parallax measurements for stars. Indirectly, it is also driven by the requirements on the coadded survey depth and the minimum number of exposures required by weak lensing science (Chapter 14) to average over systematics in the point-spread function.
2. *Image quality* should maintain the limit set by the atmosphere (the median free-air seeing is 0.7 arcsec in the  $r$  band at the chosen site, see Figure 2.3), and not be degraded appreciably by the hardware. In addition to stringent constraints from weak lensing, the requirement for good image quality is driven by the required survey depth for point sources and by image differencing techniques.
3. *Photometric repeatability* should achieve 5 millimag precision at the bright end, with zeropoint stability across the sky of 10 millimag and band-to-band calibration errors not larger than 5 millimag. These requirements are driven by the need for photometric redshift accuracy, the separation of stellar populations, detection of low-amplitude variable objects (such as eclipsing planetary systems), and the search for systematic effects in Type Ia supernova light curves.
4. *Astrometric precision* should maintain the limit set by the atmosphere of about 10 mas rms per coordinate per visit at the bright end on scales below 20 arcmin. This precision is driven by the desire to achieve a proper motion uncertainty of  $0.2 \text{ mas yr}^{-1}$  and parallax uncertainty of 1.0 mas over the course of a 10-year survey (see § 1.6.1).

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<sup>1</sup><http://www.lsst.org/Science/docs.shtml>

5. *The single visit exposure time* (including both exposures in a visit) should be less than about a minute to prevent trailing of fast moving objects and to aid control of various systematic effects induced by the atmosphere. It should be longer than  $\sim 20$  seconds to avoid significant efficiency losses due to finite readout, slew time, and read noise (§ 1.6.2).
6. *The filter complement* should include six filters in the wavelength range limited by atmospheric absorption and silicon detection efficiency (320–1050 nm), with roughly rectangular filters and no large gaps in the coverage, in order to enable robust and accurate photometric redshifts and stellar typing. An SDSS-like  $u$  band is extremely important for separating low-redshift quasars from hot stars and for estimating the metallicities of F/G main sequence stars. A bandpass with an effective wavelength of about 1 micron will enable studies of sub-stellar objects, high-redshift quasars (to redshifts of  $\sim 7.5$ ), and regions of the Galaxy that are obscured by interstellar dust.
7. *The revisit time distribution* should enable determination of orbits of Solar System objects and sample SN light curves every few days, while accommodating constraints set by proper motion and trigonometric parallax measurements.
8. *The total number of visits* of any given area of sky, when summed over all filters, should be of the order of 1,000, as mandated by weak lensing science, the asteroid survey, and proper motion and trigonometric parallax measurements. Studies of variable and transient sources of all sorts also benefit from a large number of visits.
9. *The coadded survey depth* should reach  $r \sim 27.5$  ( $5\sigma$ , point source), with sufficient signal-to-noise ratio in other bands to address both extragalactic and Galactic science drivers.
10. *The distribution of visits per filter* should enable accurate photometric redshifts, separation of stellar populations, and sufficient depth to enable detection of faint extremely red sources (e.g., brown dwarfs and high-redshift quasars). Detailed simulations of photometric redshift estimators (see § 3.8) suggest an approximately flat distribution of visits among bandpasses (because the system throughput and atmospheric properties are wavelength-dependent, the achieved depths are different in different bands). The adopted time allocation (see Table 1.1) gives a slight preference to the  $r$  and  $i$  bands because of their dominant role in star/galaxy separation and weak lensing measurements.
11. *The distribution of visits on the sky* should extend over at least  $\sim 20,000$  deg<sup>2</sup> to obtain the required number of galaxies for weak lensing studies, to study the distribution of galaxies on the largest scales and to probe the structure of the Milky Way and the Solar System, with attention paid to include “special” regions such as the ecliptic, the Galactic plane, and the Large and Small Magellanic Clouds.
12. *Data processing, data products, and data access* should enable efficient science analysis. To enable a fast and efficient response to transient sources, the processing latency for objects that change should be less than a minute after the close of the shutter, together with a robust and accurate preliminary classification of reported transients.

Remarkably, even with these joint requirements, none of the individual science programs is severely over-designed. That is, despite their significant scientific diversity, these programs are highly compatible in terms of desired data characteristics. Indeed, any one of the four main science drivers: the Solar System inventory, mapping the Milky Way, transients, and dark energy/dark matter, could be removed, and the remaining three would still yield very similar requirements for

most system parameters. As a result, the LSST system can adopt a highly efficient survey strategy where *a single data set serves most science programs* (instead of science-specific surveys executed in series). One can think of this as *massively parallel astrophysics*.

About 90% of the observing time will be devoted to a uniform deep-wide-fast (main) survey mode. All scientific investigations will utilize a common database constructed from an optimized observing program. The system is designed to yield high image quality as well as superb astrometric and photometric accuracy. The survey area will cover 30,000 deg<sup>2</sup> with  $\delta < +34.5$  deg, and will be imaged many times in six bands, *ugrizy*, spanning the wavelength range 320–1050 nm. Of this 30,000 deg<sup>2</sup>, 20,000 deg<sup>2</sup> will be covered with a deep-wide-fast survey mode, with each area of sky covered with 1000 visits (summed over all six bands) during the anticipated 10 years of operations. This will result in measurements of 10 billion stars to a depth of 27.7 mag and photometry for a roughly equal number of galaxies. The remaining 10% of the observing time will be allocated to special programs such as a Very Deep + Fast time domain survey, in which a given field is observed for an hour every night.

The uniform data quality, wavelength coverage, deep 0.7 arcsec imaging over tens of thousands of square degrees together with the time-domain coverage will be unmatched. LSST data will be used by a very large fraction of the astronomical community – this is a survey for everyone.

## 1.6 Defining the Telescope Design Parameters

Given the science requirements listed in the previous section, we now discuss how they are translated into constraints on the main system design parameters: the aperture size, the survey lifetime, and the optimal exposure time. The basic parameters of the system are outlined in [Table 1.1](#).

### 1.6.1 The Aperture Size

The product of the system’s étendue and the survey lifetime, for given observing conditions, determines the sky area that can be surveyed to a given depth. The LSST field-of-view area is set to the practical limit possible with modern optical designs, 10 deg<sup>2</sup>, determined by the requirement that the delivered image quality be dominated by atmospheric seeing at the chosen site (Cerro Pachón in Northern Chile; § 2.2). A larger field-of-view would lead to unacceptable deterioration of the image quality. This leaves the primary mirror diameter and survey lifetime as free parameters. Our adopted survey lifetime is ten years. Shorter than this would imply an excessively large and expensive mirror (15 meters for a three-year survey and 12 meters for a five-year survey), while a much smaller telescope would require much more time to complete the survey with the associated increase in operations cost and evolution of the science goals.

The primary mirror size is a function of the required survey depth and the desired sky coverage. Roughly speaking, the anticipated science outcome scales with the number of detected sources. For practically all astronomical source populations, in order to maximize the number of detected

<b>Main System and Survey Characteristics</b>	
Étendue	319 m <sup>2</sup> deg <sup>2</sup>
Area and diameter of field of view	9.6 deg <sup>2</sup> (3.5 deg)
Effective clear aperture (on-axis)	6.7 m (accounting for obscuration)
Wavelength coverage (full response)	320-1080 nm
Filter set	<i>u, g, r, i, z, y</i> (five concurrent in camera at a time)
Sky coverage	20,000 deg <sup>2</sup> (Main Survey)
<b>Telescope and Site</b>	
Configuration	three-mirror, Alt-azimuth
Final f/ratio; plate scale	f/1.23 50 microns/arcsec
Physical diameter of optics	M1: 8.4m M2: 3.4m M3: 5.02 m
First camera lens; focal plane diameter	Lens: 1.55 m field of view: 63 cm
Diameter of 80% encircled energy spot due to optics	<i>u</i> : 0.26'' <i>g</i> : 0.26'' <i>r</i> : 0.18'' <i>i</i> : 0.18'' <i>z</i> : 0.19'' <i>y</i> : 0.20''
<b>Camera</b>	
Pixel size; pixel count	10 microns (0.2 arcsec); 3.2 Gpixels
Readout time	2 sec
Dynamic range	16 bits
Focal plane device configuration	4-side buttable, > 90% fill factor
Filter change time	120 seconds
<b>Data Management</b>	
Real-time alert latency	60 seconds
Raw pixel data/night	15 TB
Yearly archive rate (compressed)	Images: 5.6 PB; Catalogs: 0.6 PB
Computational requirements	Telescope: <1 Tflop; Base facility: 30 Tflop; Archive Center: 250 Tflop by year 10
Bandwidth:	Telescope to base: 40 Gbits/sec Base to archive: 2.5 Gbits/sec avg
<b>System Capability</b>	
Single-visit depths (point sources; 5 $\sigma$ )	<i>u</i> : 23.9 <i>g</i> : 25.0 <i>r</i> : 24.7 <i>i</i> : 24.0 <i>z</i> : 23.3 <i>y</i> : 22.1 AB mag
Baseline number of visits over 10 years	<i>u</i> : 70 <i>g</i> : 100 <i>r</i> : 230 <i>i</i> : 230 <i>z</i> : 200 <i>y</i> : 200
Coadded depths (point sources; 5 $\sigma$ )	<i>u</i> : 26.3 <i>g</i> : 27.5 <i>r</i> : 27.7 <i>i</i> : 27.0 <i>z</i> : 26.2 <i>y</i> : 24.9 AB mag
Photometry accuracy (rms mag)	repeatability: 0.005; zeropoints: 0.01
Astrometric accuracy at $r = 24$ (rms)	parallax: 3 mas; proper motion: 1 mas yr <sup>-1</sup>

Table 1.1: LSST System Parameters

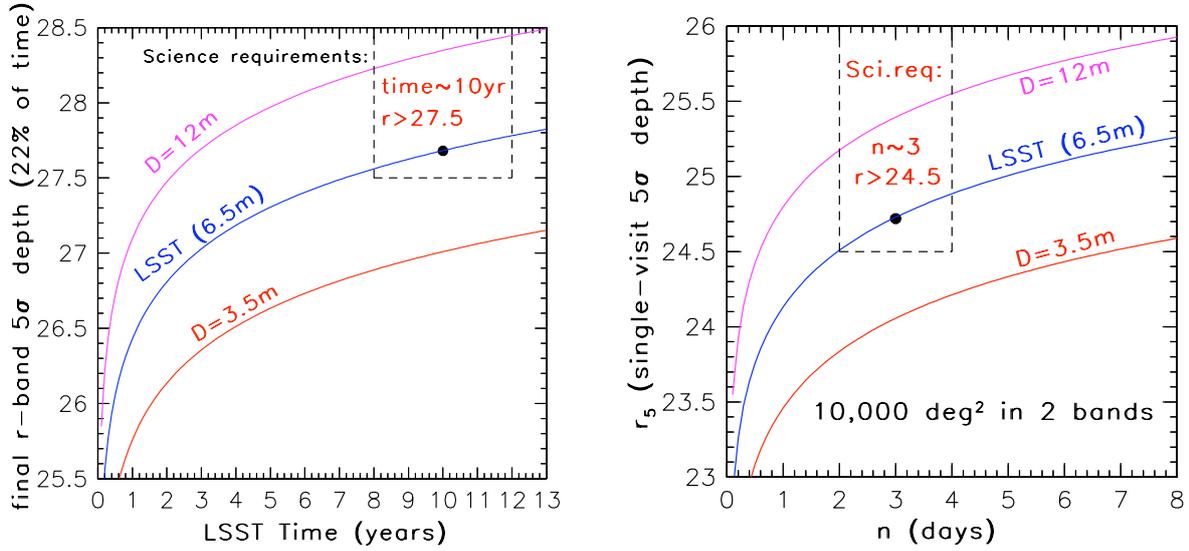


Figure 1.1: (a) The coadded depth in the  $r$  band (AB magnitudes) vs. the effective aperture and the survey lifetime. It is assumed that 22% of the total observing time (corrected for weather and other losses) is allocated for the  $r$  band, and that the ratio of the surveyed sky area to the field-of-view area is 2,000. (b) The single-visit depth in the  $r$  band ( $5\sigma$  detection for point sources, AB magnitudes) vs. revisit time,  $n$  (days), as a function of the effective aperture size. With a coverage of  $10,000 \text{ deg}^2$  in two bands, the revisit time directly constrains the visit exposure time,  $t_{vis} = 10n$  seconds; these numbers can be directly scaled to the  $20,000 \text{ deg}^2$  and six filters of LSST. In addition to direct constraints on optimal exposure time,  $t_{vis}$  is also driven by requirements on the revisit time,  $n$ , the total number of visits per sky position over the survey lifetime,  $N_{visit}$ , and the survey efficiency,  $\epsilon$  (see Equation 1.3). Note that these constraints result in a fairly narrow range of allowed  $t_{vis}$  for the main deep-wide-fast survey. From Ivezić et al. (2008).

sources, it is more advantageous to maximize first the area and then the detection depth.<sup>2</sup> For this reason, the sky area for the main survey is maximized to its practical limit,  $20,000 \text{ deg}^2$ , determined by the requirement to avoid large airmasses ( $X \equiv \sec(\text{zenith distance})$ ), which would substantially deteriorate the image quality and the survey depth. With the adopted field-of-view area, the sky coverage and the survey lifetime fixed, the primary mirror diameter is fully driven by the required survey depth. There are two depth requirements: the final (coadded) survey depth,  $r \sim 27.5$ , and the depth of a single visit,  $r \sim 24.5$ . The two requirements are compatible if the number of visits is several hundred per band, which is in good agreement with independent science-driven requirements on the latter. The required coadded survey depth provides a direct constraint, independent of the details of survey execution such as the exposure time per visit, on the minimum *effective* primary mirror diameter of 6.5 m, as illustrated in Figure 1.1. This is the effective diameter of the LSST taking into account the actual throughput of its entire optical system.

<sup>2</sup>The number of sources is proportional to area, but rises no faster than Euclidean with survey depth, which increases by 0.4 magnitude for a doubling of exposure time in the sky-dominated regime; see Nemiroff (2003) for more details.

### 1.6.2 The Optimal Exposure Time

The single visit depth depends on both the primary mirror diameter and the chosen exposure time,  $t_{\text{vis}}$ . In turn, the exposure time determines the time interval to revisit a given sky position and the total number of visits, and each of these quantities has its own science drivers. We summarize these simultaneous constraints in terms of the single-visit exposure time:

- The single-visit exposure time should not be longer than about a minute to prevent trailing of fast solar system moving objects, and to enable efficient control of atmospheric systematics.
- The mean revisit time (assuming uniform cadence) for a given position on the sky,  $n$ , scales as

$$n = \left( \frac{t_{\text{vis}}}{10 \text{ sec}} \right) \left( \frac{A_{\text{sky}}}{10,000 \text{ deg}^2} \right) \left( \frac{10 \text{ deg}^2}{A_{\text{FOV}}} \right) \text{ days}, \quad (1.1)$$

where two visits per night are assumed (this is needed to get velocity vectors for main belt and near-Earth asteroids), and the losses for realistic observing conditions have been taken into account (with the aid of the Operations Simulator described in § 3.1). Science drivers such as supernovae and moving objects in the Solar System require that  $n < 4$  days, or equivalently  $t_{\text{vis}} < 40$  seconds for the nominal values of  $A_{\text{sky}}$  and  $A_{\text{FOV}}$ .

- The number of visits to a given position on the sky,  $N_{\text{visit}}$ , with losses for realistic observing conditions taken into account, is given by

$$N_{\text{visit}} = \left( \frac{3000}{n} \right) \left( \frac{T}{10 \text{ yr}} \right), \quad (1.2)$$

where  $n$  is the mean time, in days, between visits to a given position. The requirement  $N_{\text{visit}} > 800$  again implies that  $n < 4$  and  $t_{\text{vis}} < 40$  seconds if the survey lifetime,  $T$  is about 10 years.

- These three requirements place a firm upper limit on the optimal visit exposure time of  $t_{\text{vis}} < 40$  seconds. Surveying efficiency (the ratio of open shutter time to the total time spent per visit) considerations place a lower limit on  $t_{\text{vis}}$  due to finite read-out and slew time. The read-out time of the camera is in fact two seconds for each exposure (§ 2.4), and the slew and settle time is set to five seconds, including the readout time for the second exposure in a visit:

$$\epsilon = \frac{t_{\text{vis}}}{t_{\text{vis}} + 9 \text{ sec}}. \quad (1.3)$$

To maintain efficiency losses below 30% (i.e., at least below the limit set by weather), and to minimize the read noise impact,  $t_{\text{vis}}$  should be less than 20 seconds.

Taking these constraints simultaneously into account, as summarized in Figure 1.1, yields the following reference design:

- A primary mirror effective diameter of  $\sim 6.5$  m. With the adopted optical design, described below, this effective diameter corresponds to a geometrical diameter of  $\sim 8$  m. Motivated by the characteristics of the existing equipment at the Steward Mirror Laboratory, which has cast the primary mirror, the adopted geometrical diameter is set to 8.4 m.
- A visit exposure time of 30 seconds (using two 15-second exposures to efficiently reject cosmic rays), yielding  $\epsilon = 77\%$ .

- A revisit time of three days on average per 10,000 deg<sup>2</sup> of sky (i.e., the area visible at any given time of the year), with two visits per night (particularly useful for establishing proper motion vectors for fast moving asteroids).

To summarize, the chosen primary mirror diameter is the minimum diameter that simultaneously satisfies the depth ( $r \sim 24.5$  for single visit and  $r \sim 27.5$  for coadded depth) and cadence (revisit time of 3-4 days, with 30 seconds per visit) constraints described above.

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