Supporting Note for HEPAP Subcommittee: LSST Science Impact and Readiness

The LSST Project is a partnership among the National Science Foundation (NSF), the Department of Energy (DOE) Office of Science, and public and private organizations in the United States and abroad. The DOE LSST Camera Project is responsible for the development of a 3.2 gigapixel digital camera for LSST. In collaboration with the entire LSST Project, we are pleased to provide this supporting note, and hope it will assist the High Energy Physics Advisory Panel form its recommendations to the DOE Office of Science. We believe LSST, which is planned to begin science survey operations in 2021, promises to be one of the world's major scientific facilities, and will provide an unprecedented public astrophysics data set for use in numerous areas of inquiry, particularly dark energy science, a research field classified as "absolutely central" in the 2003 report, "High-Energy Physics Facilities Recommended for the DOE Office of Science".

The first section of this note, **LSST Science**, addresses the following questions:

- What science will be enabled by LSST?
- What agencies have endorsed the LSST Project?
- How will LSST provide data to the scientific community at large?
- What plans are in place for using LSST data for dark energy science?

The second section, **LSST Readiness**, addresses:

- What is the design of the LSST?
- What stage of design or implementation has each LSST subsystem reached?
- Is LSST ready for construction?

LSST Science: What is the Likely Impact?

The Large Synoptic Survey Telescope (LSST) will be a large-aperture, wide-field, optical imaging facility designed to address some of the most pressing questions about the structure and evolution of the universe and the objects within it. What is the mysterious dark energy that is driving the acceleration of the cosmic expansion? What is dark matter, how is it distributed, and how do its properties affect the formation of stars, galaxies, and larger structures? How did the Milky Way form, and how has its present configuration been modified by mergers with smaller bodies over cosmic time? What is the nature of the outer regions of the solar system? Is it possible to make a complete inventory of smaller bodies in the solar system, especially the potentially hazardous asteroids that could someday impact the Earth? Are there new exotic and explosive phenomena in the universe that have not yet been discovered?

These are profound questions, and yet the concept behind the design of the LSST is remarkably simple: conduct a deep survey over an enormous area of sky; do it with a frequency that enables repeat exposures of every part of the sky every few nights in multiple bands; and continue in this mode for ten years to achieve astronomical catalogs thousands of times larger than have ever previously been compiled. The essence of the LSST is wide, fast, deep.

<u>Overview of Science Enabled by LSST</u>

Superior survey capability will open new avenues of research. In formulating the requirements for the LSST, the initial focus was on four scientific topics:

- Dark Energy and Dark Matter
- Hazardous Asteroids and the Remote Solar System
- The Transient Optical Sky
- The Formation and Structure of the Milky Way

These four science topics were chosen because they are the focus of cutting edge research that spans the universe from our own local neighborhood to distant galaxies, the formation of the solar system, the evolution of galactic structure, and cosmology. The LSST Science Book [1], which was authored by 245 scientists who are currently working with the LSST Project, describes many of these programs in detail.

Each of these four themes itself encompasses a variety of analyses, with varying sensitivity to instrumental and system parameters. These themes fully exercise the technical capabilities of the system, such as photometric and astrometric accuracy and image quality. Somewhat surprisingly, all four themes can be addressed with a common survey, i.e. a single database that is amenable to a set of extremely diverse analyses. In Table 1 below, we summary these requirements at a high level. Further detail can be found in the LSST Science Requirements Document, which is available at http://www.lsst.org/lsst/science/survey_requirements.

About 90% of LSST observing time will be devoted to a deep, wide, fast (main) survey mode. The working paradigm is that all scientific investigations will utilize a common database constructed from an optimized observing program.

Survey Property	Performance
Main Survey Area	18000 $degrees^2$
Total visits per unit area	825
Filter set	6 filters (ugrizy) from 320-1050 nm
Single visit	2x15 second exposures
Single visit limiting magnitude	u = 23.9; g = 25.0; r = 24.7; l = 24.0; z = 23.3; y = 22.1
Photometric calibration	< 1% repeatability, absolute, & colors
Median delivered image quality	~0.7 arcsec. FWHM
Transient processing latency	< 60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

Table 1: LSST survey requirements

Major Agency Endorsements

In its decadal survey "ASTRO 2010 - New Worlds, New Horizons in Astronomy and Astrophysics" [2], the NRC identified LSST as the top-ranked large ground-based initiative, noting that the ranking was a result of "(1) its compelling science case and capacity to address so many of the science goals of this survey and (2) its readiness for submission to the MREFC process as informed by its technical maturity, the survey's assessment of risk, and appraised construction and operations costs."

Because of its broad scientific potential, the development of LSST has also received strong endorsements in three other influential National Academy of Sciences/National Research Council reports:

- “Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century” [3]: Reviewed frontier research at the interface of physics and astronomy. Highlighted the capabilities of LSST as a probe of dark energy and dark matter.
- “New Frontiers in Solar System Exploration” [4]: Reviewed the current status of solar system research and outlined a program of investment for the future. Endorsed LSST for its ability to survey moving objects in the solar system.
- “Astronomy and Astrophysics in the New Millennium” [5]: Reviewed major new initiatives in all areas of astronomy and astrophysics. Endorsed LSST as a high-priority major new project in ground-based astronomy.

As a dark energy experiment, the LSST project has also attracted the interest of the particle physics community. The Dark Energy Task Force (DETF), commissioned jointly by the Astronomy and Astrophysics Advisory Committee (AAAC) and the HEPAP, concluded that a Stage IV Large Survey Telescope (modeled on LSST) could make a major advance in our understanding of dark energy, especially if subtle systematic errors can be brought under control [6].

On the basis of the DETF report and the results of the LSST Conceptual Design Review, the Particle Physics Project Prioritization Panel (P5), recommended in 2008 that "DOE support the ground-based LSST program, in coordination with NSF" [7].

Model for Data Access

LSST has been conceived as a public facility. The image archive that it will produce, and the associated object catalogs that are generated from those data, will be made available to the U.S. and Chilean scientific communities with no proprietary period. The LSST data management system will provide user-friendly tools to access this database and to support user-initiated queries run on LSST computers at the data access centers. We expect that the majority of LSST discoveries will come from research astronomers with no formal affiliation to the project, from students, and from interested amateurs, intrigued by the access to the universe that this facility uniquely provides. Because of its interest in enabling access to LSST images by the general public, the Google Corporation has joined the LSST team.

The Sloan Digital Sky Survey (SDSS) provides a good example for how the scientific community can be effective in working with large, publicly available astronomical data sets. Over 60% of the refereed papers based on SDSS data to date have been written by people from outside the project and include many of the most high-profile results that have come from the facility.

LSST, Dark Energy Research and the LSST Dark Energy Science Collaboration (DESC)

While high-profile discoveries are likely to come from outside the LSST Project, it is clear that many of the highest priority LSST science investigations will require organized teams of professionals working together to optimize science analyses and to assess the importance of systematic uncertainties on the derived results. To meet this need, science collaborations have already been established by the project in core science areas. One such collaboration, the LSST Dark Energy Science Collaboration (DESC), has been formed to plan for the tremendous opportunity represented by LSST.

Historically, our understanding of the cosmic frontier has progressed in step with the size of our astronomical surveys, and in this respect, LSST promises to be a major advance: its survey coverage will be approximately ten times greater than that of the Stage III Dark Energy Survey. Survey size is a straightforward measure of scientific gain. A less agnostic metric with which to judge dark energy probes is the Figure of Merit proposed by the Dark Energy Task Force: the inverse of the area of the 1-sigma ellipse in the w_0–w_a plane marginalized over other cosmological parameters. Figure 1 shows these projected constraints from four LSST probes: weak lensing (WL), baryonic acoustic oscillations (BAO), cluster counts, and supernovae (SNe). The WL and BAO results are based on Zhan [8] and Zhan et al. [9], the cluster counting result is from Fang & Haiman [10], and the supernova result is based on [11]. While absolute projections are uncertain due to some residual systematic uncertainties, the relative gain in the Figure of Merit of LSST over Stage III surveys consistently comes in at a factor of 5-10.

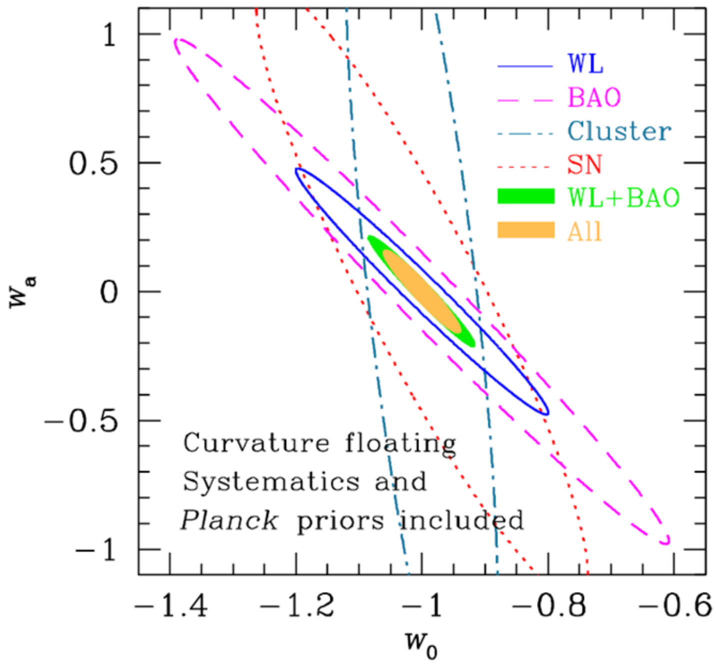

Figure 1: Joint w_0–w_a constraints from LSST WL (solid line), BAO (dashed line), cluster counting (dash-dotted line), supernovae (dotted line), joint BAO and WL (green shaded area), and all combined (yellow shaded area). The BAO and WL results are based on galaxy–galaxy, galaxy–shear, and shear–shear power spectra only. Adding other probes such as strong lensing time delay, and higher-order galaxy and shear statistics will further improve the constraints. For comparison, the areas of the error ellipses of Stage III dark energy experiments would be about 10 times larger than that of LSST (for a comparison of WL+BAO results, see [8]).

In its white paper [12], the DESC has described plans to develop a robust analytical framework for dark energy science and a comprehensive three-year work plan for implementing that framework. The analyses required for dark energy research are sensitive to a large number of potential systematic uncertainties that must be identified, quantified, and minimized in order for the DE investigations to achieve their full potential. In addition, new algorithms must be developed and tested to enable those analyses, and an efficient computational and software framework must be established to perform the necessary calculations. The DESC was created to coordinate the extensive research effort needed well in advance of the onset of data taking.

The DESC is organized around five probes of dark energy enabled by the LSST data. These include the four techniques (weak lensing, large scale structure, Type Ia supernovae, and galaxy clusters) described in the 2006 Report of the Dark Energy Task Force [6]. The DESC will identify and work to minimize the most significant systematic uncertainties that limit the sensitivity of each probe, beginning with those that are most time-urgent. The DESC also plans to address high priority tasks that cut across all five probes. These include calibration strategies for photometric redshifts; cosmological simulations, simulated catalogs, and photon-level simulations with the fidelity needed to fully assess and exploit each probe of dark energy with the LSST; cross working group tools for data quality assessment and detection of systematics; and, a realistic data model, software framework, and computing model to fully address DE science.

LSST Readiness: What is the Status of the LSST Project?

A large and integrated team of scientists and engineers from the particle physics and astronomy communities has been assembled to translate the LSST concept into an achievable system design. An extensive research and development program has been funded partly from DOE funds, partly from the National Science Foundation, and partly by in-kind resources from private donors and partner institutions. The development effort, which has been underway for a number of years and will continue until the onset of construction, includes structural, thermal, and optical analyses of all key hardware subsystems, vendor interactions to determine manufacturability, explicit prototyping of high-risk hardware and software elements, and extensive systems engineering studies. Over 100 technical personnel at a range of institutions are currently engaged in this program.

The LSST team is distributed geographically but managed as a single project, according to formal project management control processes as required by both the NSF and DOE. The Program Management Office is based in Tucson along with the Systems Engineering group to interface with the each of the subsystem managers and technical teams distributed throughout the country and abroad. The camera team is managed at SLAC but has key science and engineering staff at Brookhaven, LLNL, and other institutions across the country and France. The Data Management team is at member LSST organizations such as the University of Washington, Princeton University, the Infrared Processing and Analysis Center (IPAC) at the California Institute of Technology, SLAC and the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign to align with the work required for the final construction preparation and the construction work itself. The LSST team is in place and ready to ramp to full staff upon completion of the Final Design Phase.

The total requested construction budget is $626 M in federal funds. The DOE MIE portion for the Camera is $160M and the NSF portion for the rest of the LSST Project is $466 M. These budgets are fully loaded, cast in "then-year" dollars, and include 27% contingency overall, with 40% contingency on the Camera effort. According to the preliminary baseline plan, which is consistent with funding profiles supplied by DOE and NSF, science verification will begin in October, 2020, and the full survey will begin in October, 2021. The costs were vetted during the DOE CD-1 review (i.e., readiness to begin Camera preliminary design) in November 2011 and the NSF Cost Review in May 2012. The Camera is planning to begin phased 'construction' by initiating long lead procurements after securing CD-3a approval in FY2014. The operation costs to conduct the survey and carry out the data management tasks are estimated to be $37.2M/year. According to the NSF/DOE MOU, these costs will be funded by NSF at $19M/year and by the DOE at $9M/year, with the remainder contributed by international affiliates. The DOE budget includes an additional $6M/year for science operations. All operations costs are in 2011USD.

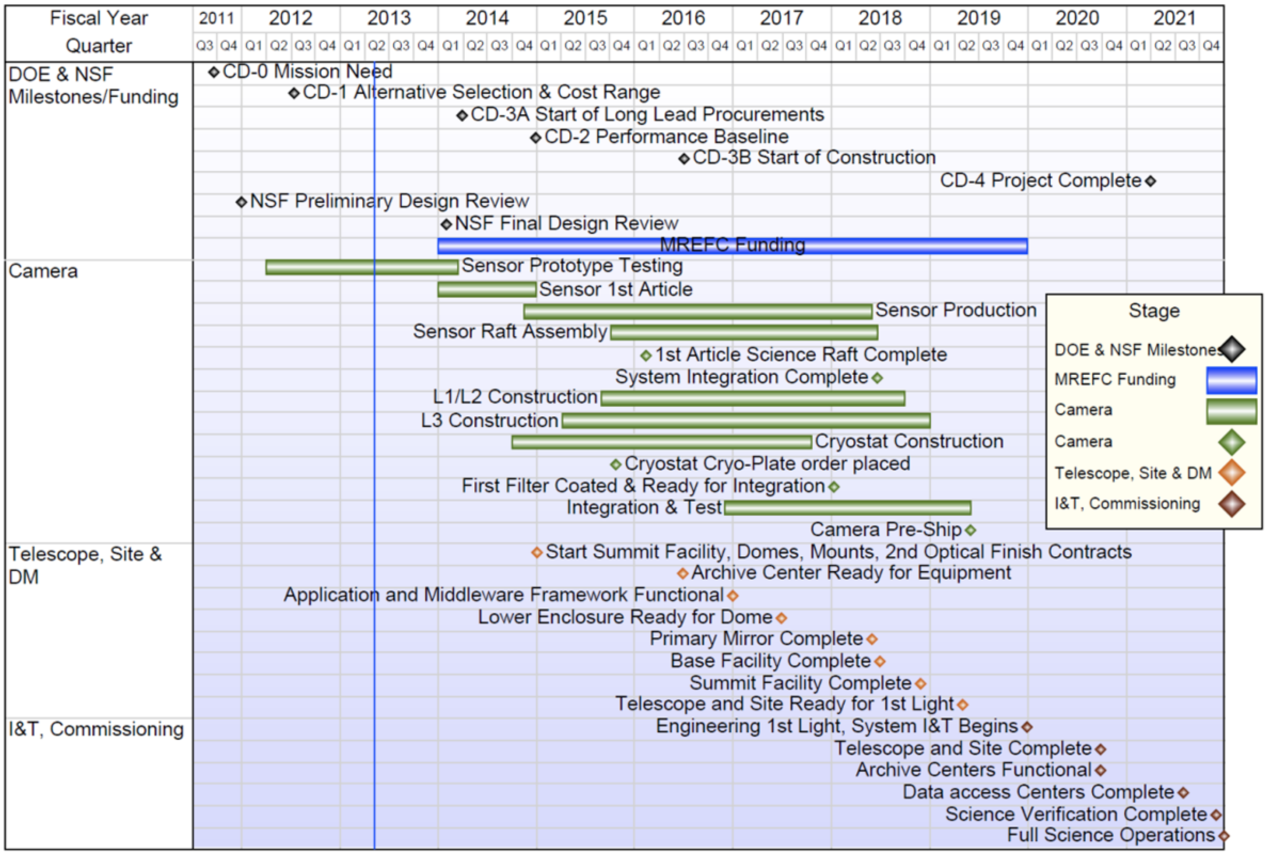

Figure 2: High-level milestones for the LSST Project.

Design of LSST

The LSST optical design has been optimized to yield a very large field of view (9.6 deg^2), with seeing-limited image quality, across a wide wavelength band (320-1050 nm). Incident light is collected by the primary mirror, which is an annulus with an outer diameter of 8.4 m, then reflected to a 3.4-m convex secondary, onto a 5.0-m concave tertiary, and finally into three refractive lenses in a camera. This is achieved with an innovative approach that positions the tertiary mirror inside the primary mirror annulus ring, making it possible to fabricate the mirror pair from a single monolithic blank using borosilicate glass. The secondary is a thin meniscus mirror, fabricated in an ultra low expansion material. All three mirrors will be actively supported to control wavefront distortions introduced by gravitational and environmental stresses on the telescope.

Based on the recommendation of an international site selection committee, the **LSST Observatory** will be sited atop Cerro Pachón in northern Chile, near the Gemini South and SOAR telescopes. This is a developed NSF site, administered by the Associated Universities for Research in Astronomy (AURA). The site architect's rendering of the facility on this site is shown in Figure 3.

Figure 3: Artist's rendering of the LSST and dome enclosure with the attached summit support buildings and the LSST calibration telescope shown on an adjacent peak.

The **LSST Camera** provides a 3.2-gigapixel flat focal plane array, tiled by 4K x 4K CCD sensors with 10-μm square pixels. The sensors are deep-depleted, back-illuminated devices with a highly segmented architecture that enables the entire array to be read out in 2 seconds. Detectors are grouped into rafts in 3 x 3 arrays, each containing its own dedicated front-end and back-end electronics boards. The rafts are mounted on a silicon carbide grid inside a vacuum cryostat, with an intricate thermal control system that maintains the CCDs at an operating temperature of -100C.

The entrance window to the cryostat is the third of the three refractive lenses in the camera. The other two lenses are mounted in an optics structure at the front of the camera body, which also contains a mechanical shutter and a carousel assembly that holds five large optical filters. A sixth optical filter can replace any of the five via a procedure accomplished during daylight hours.

The **LSST Telescope** mount is a compact, stiff structure with a fundamental frequency of 8 Hz, which is crucial for achieving the fast slew-and-settle times that the survey strategy requires. The telescope sits on a concrete pier within a carousel dome that is 30 m in diameter. The dome has been designed to reduce dome seeing (local air turbulence that can distort images) and to maintain a uniform thermal environment over the course of the night.

The rapid cadence of the LSST observing program will produce -15 terabytes of image data per night, leading to a total image archive over the ten years of operations of several tens of petabytes. Processing such an enormous volume of data, converting the raw images into a faithful representation of the universe and archiving the results in useful form for a broad community of users is a major challenge for the project. The **LSST Data Management** system is configured in three layers: an infrastructure layer consisting of the computing, storage, and networking hardware and system software; a middleware layer, which handles distributed processing, data access, user interface, and system operations services; and an applications layer, which includes the data pipelines and products and the science data archives. There will be both base computing facilities and a central archive facility and multiple data access centers. The data will be transported over existing high-speed optical fiber links from South America to the United States.

What is the Design Maturity and Status of Each LSST Subsystem?

The NSF is responsible for site and telescope development and the data management system, while the DOE is responsible for development and delivery of the large-format camera. Private contributions have already been used for fabrication of the mirrors and site preparation in Chile. In April 2012, the Camera Project received "Critical Decision 1" approval by the DOE to move into the detailed engineering design, schedule, and budget phase. In July 2012, the National Science Board of the NSF approved the LSST as a Major Research Equipment and Facilities Construction (MREFC) project, allowing the NSF Director to advance the project to the final design stage and include funds for LSST construction in a future budget request. If all continues as planned, construction will begin in 2014 and is anticipated to last five years, followed by a two-year commissioning period before the start of the survey in 2021.

The technical details of the program are well advanced and ready for construction. To develop and manage the overall technical scope of the LSST, the Systems Engineering team has implemented model-based systems engineering using the System Modeling Language (SysML). The SysML database from the is the control point for both system and subsystem requirements and interfaces and provides the distributed LSST team a single common database from which to work. LSST has an Operations Simulator in place that provides a dynamic model of the LSST hardware, site-specific weather patterns, and astro-climate coupled with specific science-driven data properties to simulate the survey temporal cadence and sky coverage. LSST has also developed an extensible framework, an Image Simulator, to produce high fidelity simulated images that capture the individual characteristics of each image at full survey scale volumes of data using detailed physical models of the observing system properties (atmosphere, telescope, and camera) and object catalogs designed to match the depths and properties of LSST's reach. Each of these simulation tools is instrumental in supporting the effective development of the system to meet the Science goals and to support early preparation by science teams to prepare for the LSST survey.

Camera Readiness

The LSST Camera Project will be ready to execute long-lead procurements by 2014. Camera subsystem designs were successfully reviewed at CD-1 and found to be technically advanced for a project at such a milestone. Key technical risks – particularly those related to the sensors, sensor readout, optics and focal plane refrigeration - have been mitigated through design, analysis, prototyping and testing. The Camera sensors are state of the art thick fully-depleted Charge-Coupled Devices (CCDs), on high-rho silicon, using 16 amplifiers that achieve broad spectral coverage, minimal charge spreading, fast readout (3.2 gigapixels in 2 seconds) and low noise. These devices have been under development since 2008 and recent prototype results have demonstrated that they fully meet LSST requirements for scientific imaging. The project continues to advance on the end-to-end readout of the prototype CCDs, exercising the entire acquisition chain from sensor to front end electronics, on to the data acquisition system and finally to a prototype data processing pipeline provided by the LSST Data Management team. Several vendors have expressed interest in fabricating the camera's large refractive optics and have reviewed our current designs; the project is ready to move to a design build contract. For refrigeration of the camera focal plane (the largest in astronomy), a novel high-capacity mixed-refrigerant system has been prototyped; its cooling capacity has proven to be enormous, representing a significant advance for non-flammable mixed-refrigerant technology. Risk mitigation in these key areas leaves the Camera Project well-prepared to begin procurement and fabrication.

Telescope and Site Readiness

The Telescope and site portion of the project is well positioned for construction with both detailed designs, privately funded long lead optics development, and a site preparation. LSST chose the Cerro Pachón site for the telescope in 2005. Pursuant to Chilean law, all necessary environmental declarations have been submitted to authorities, and AURA, on behalf of LSST, has been granted all necessary permits to build and operate the LSST facility on Cerro Pachón. With the permits, and LSST Corporation non-federal funds, the team has been able to prepare the site with initial excavation that supports detailed investigation of the rock structure and the final summit facility design. The team has been working with an architect for several years on the summit facility and will have the 100% drawing package in the May 2013 timeframe. All three mirrors for the telescope are already fabricated and, in the case of the Primary/tertiary mirror, nearing full optical polishing.

The final development work is focused on completing the final designs as need for a full construction start and a series of risk mitigation activities. The team is in place, the site and permits are ready, the designs are mature and the plans are in place to ramp-up the activity to full construction.

Data Management Readiness

The LSST Data Management System has been designed and prototyped to provide fully-calibrated public data to the user community using code that will be open source and fully available to the research community. The nature, quality, and volume of LSST data will be unprecedented, featuring petascale storage, terascale computing, and gigascale communications. The Data Management team is organizationally in place drawing on community expertise to form a highly qualified team. The team has already produced hundreds of thousands of lines of C++ and Python code and object classes where 60% of the functional capability has been prototyped and tested through a series of bi-annual data challenges. The existing code stack is already in use for various tests on existing data.

Is LSST Ready for Construction?

The DOE LSST Camera project received CD-0 [13] approval in March 2011 and CD-1 [14] in April 2012. The project is on track to start construction, with long lead procurements to follow CD-3a in 2014. The LSST MREFC project is prepared for a full construction start in 2014.

References

1. Collaboration, L.S., et al. *LSST Science Book, Version 2.0*. ArXiv e-prints, 2009. **0912**, 201.
2. *New Worlds, New Horizons in Astronomy and Astrophysics*2010: The National Academies Press.
3. *Connecting Quarks with the Cosmos:Eleven Science Questions for the New Century*2003: The National Academies Press.
4. *New Frontiers in Solar System Exploration*2003: The National Academies Press.
5. *Astronomy and Astrophysics in the New Millennium*2001: The National Academies Press.
6. Albrecht, A., et al. *Report of the Dark Energy Task Force*. ArXiv Astrophysics e-prints, 2006. 9591.
7. Baltay, C., et. al., *US Particle Physics: Scientific Opportunities. A Strategic Plan for the Next Ten Years*, 2008, HEPAP Particle Physics Project Prioritization Panel.
8. Zhan, H., *Cosmic tomographies: baryon acoustic oscillations and weak lensing.* Journal of Cosmology and Astro-Particle Physics, 2006. **08**: p. 008.
9. Zhan, H., L. Knox, and J.A. Tyson, *Distance, Growth Factor, and Dark Energy Constraints from Photometric Baryon Acoustic Oscillation and Weak Lensing Measurements.* The Astrophysical Journal, 2009. **690**: p. 923-936.
10. Fang, W.J. and Z. Haiman, *Constraining dark energy by combining cluster counts and shear-shear correlations in a weak lensing survey.* Physical Review D, 2007. **75**(4).
11. Zhan, H., *Probing dark energy with the Large Synoptic Survey Telescope.* Relativistic Astrophysics, 2008. **966**: p. 181-184.
12. Collaboration, L.D.E.S. *Large Synoptic Survey Telescope: Dark Energy Science Collaboration*. ArXiv e-prints, 2012. **1211**, 310.
13. Mission Need Statement for a Dark Energy Stage IV Experiment(s) (DE-IV).
14. LSST Camera Project CD-1 Decision Document.