Large Synoptic Survey Telescope

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Connections between LSST Science and Particle Physics

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We are in the midst of a revolution in physics. Observing the cosmos has provided compelling evidence for physics beyond the standard model of particle physics: non-zero neutrino masses, non-baryonic dark matter, dark energy and primordial inflation. Together with ordinary matter these constituents determine the structure of the Universe. The necessary, but puzzling, connection between the inner space of quantum reality and outer space of cosmic reality will enable the discovery of new particle physics through astrophysical observations and may reconcile quantum mechanics and General Relativity in a new synthesis – a standard model of the Universe. LSST will contribute significantly to answering the following questions:

1. **What is dark energy?**
2. **What is dark matter?**
3. **What are the neutrino masses?**
4. **Was primordial inflation responsible for the origin of large-scale structure? Did it leave observable imprints that can shed light on the unification of the fundamental forces?**
5. **Can gravity be described in a unified quantum framework with the other forces?**

Precision cosmological observations will enable falsification of models covering the inflationary epoch, through the "dark ages," to the first generation of stars and galaxies, and the current cosmic acceleration. LSST will study the impact of dark energy on both the history of cosmic expansion and growth of large-scale structure using diverse techniques based on weak lensing, baryon acoustic oscillations, supernovae, galaxy clusters and strong lensing of quasars. Inconsistencies in the results may signal deficiencies in General Relativity and the need for a new theory of gravity.

Introduction and Open Questions

The standard model of particle physics allows for three doublets of quarks and leptons, and twelve gauge bosons that mediate the three forces that it describes. There is substantial evidence that the standard model is incomplete. We lack a unified description of the fundamental forces (especially gravity), and an explanation for the fermion masses, neutrino oscillations, dark matter (DM), and dark energy (DE). Many questions in cosmology bear on the same issues. Is the DE a cosmological constant? Is it homogeneous? Why is its density so much smaller than the standard model predicts? Does the DM interact with itself? Is there evidence for more species of neutrinos? Is General Relativity correct? Does cosmological inflation have a particle physics explanation? Both DM and DE produce substantial cosmological effects. Neutrinos produce smaller, but measurable, effects. Measurements of the history of the expansion of the universe and of the growth of structure have told us the densities of DM and DE, constrained the DM particle masses and the DE equation of state, and put upper limits on the neutrino masses. Because DM and DE constitute 96% of the energy content of the universe, a more precise understanding of their properties is required for the development of a more complete -- i.e., new – standard model.

OPEN QUESTIONS:

Dark Energy: The phenomenon of DE lies at the juncture of quantum mechanics and gravitation, and is evidence for physics beyond the standard model. With current physics, a straight-forward calculation of the density of dark energy yields a prediction that is 120 orders of magnitude larger than observed. Modifications of General Relativity may be required.

Dark Matter: Most supersymmetric extensions to the standard model predict the existence of a stable, weakly interacting particle that would be a dark matter candidate. Measurements of the rate of structure growth and of the details of small-scale structure will provide constraints on DM's interactions and particle masses.

Neutrinos: Neutrino mass constraints imposed by neutrino oscillations tell us that neutrinos were relativistic during early times, but that at least two neutrino species are nonrelativistic now. Consequently, neutrinos create an observable distortion of the large-scale structure. This may be the most direct path to an absolute measurement of the neutrino masses.

Inflation: Non-gaussianity in the large-scale structure will provide constraints on models of inflation that are complementary to those provided by CMB measurements.

Joint Analysis of Multiple Probes

Studies of the distribution of matter and radiation in our universe have led to the realization that new physics will be required to explain the dark matter and dark energy. At the same time, the standard model does not explain the hierarchy of fundamental particles, dark matter, or dark energy. Due to the roles that all four fundamental forces have played in the history of the universe, there are deep connections between particle physics and cosmology. Understanding the origin of dark matter and dark energy will require simultaneous progress in both particle physics and cosmology.

LSST's Role: LSST will survey the position, apparent shape, apparent magnitude and redshift of 4 billion galaxies [Abell 2009]. This survey will directly explore the physics of late-time acceleration when combined with Planck CMB data. The richness of LSST survey data will enable tests of a rich variety of general models. Models that do not change the cosmological matter-density power spectrum may be tested by precision measurements of geometry and growth of mass structure over the redshift range $0.3 < z < 1$ where the apparent late-time acceleration of the universe dominates.

Given the wide range of possible explanations for the physics of dark energy, there is strong justification for multiple tests, including purely geometrical tests such as distance vs. redshift relations, and probes of the growth of mass structure through weak gravitational lensing. Dark energy affects the history of the Hubble expansion as well as the cosmic history of mass clustering. Combining many different probes of the expansion history, as well as the growth of mass clustering to sub-percent-level precision leads to the exciting prospect of a breakthrough in our understanding. In all, there are eight different types of complementary probes of the physics of dark energy that the universal cadence LSST survey will enable, all as a function of photometric redshift [Abate 2012]. These eight probes are listed below.

Weak lensing shear cross-correlation tomography
Weak lensing magnification cross-correlation tomography
2D baryon acoustic oscillations
Type Ia Supernovae
Shear-peak statistics
Galaxy cluster counts
Time-domain tomography of QSOs and AGNs
Anisotropy of WL, BAO and SN signals

Testing Models with LSST

The LSST survey will impact our understanding of open questions in particle physics, including *dark energy, dark matter, neutrino masses, primordial inflation, and incorporation of gravity in a unified theory.*

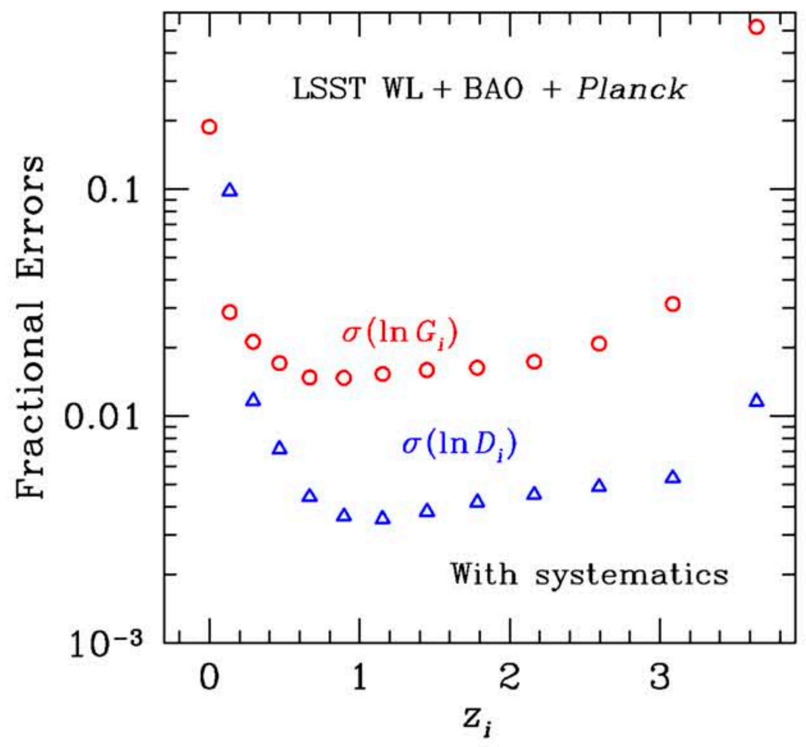
❑ The physics of dark energy will be tested by precision measurements of the growth of mass structure and of geometry (see figure below).

❑ Properties of dark matter will be gleaned from studying the evolution of structure and strong lensing of galaxies, quasars and supernovae.

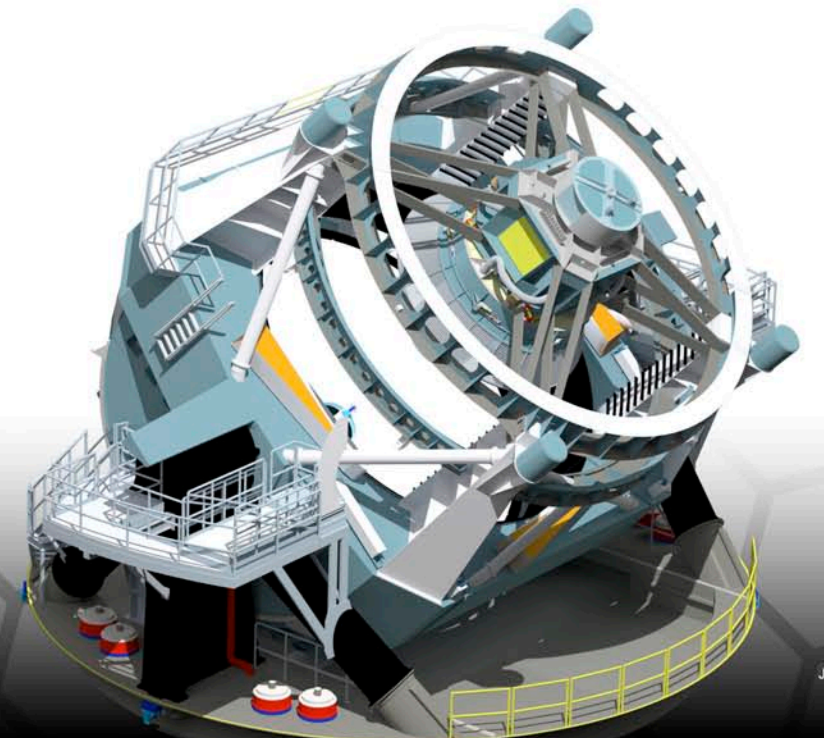
❑ Precision measurements of the matter power spectrum as a function of cosmic time will constrain the sum of neutrino masses.

❑ LSST will probe inflation using cosmic shear and the spatial power spectrum of galaxies on very large scales.

❑ Observations of the growth of mass structure and of geometry separately (see figure below) can distinguish the origins of the late-time acceleration of the universe. Is it a new component to the mass-energy or is it a new aspect of gravity [e.g., Alimi 2010]?



Theories of dark energy with more than two parameters can be confronted with the LSST data. Marginalized 1σ errors on the co-moving distance (blue triangles) and growth factor (red circles) from the joint analysis of LSST BAO and WL (galaxy–galaxy, galaxy–shear and shear–shear power spectra) with a conservative level of systematic uncertainties in the photometric redshift error distribution, and additive and multiplicative errors in the shear and galaxy power spectra. The precision in measurement opens up the possibility of measuring more general higher dimensional theories of acceleration. [From Zhan 2009.] An analysis combining all eight probes will give even higher precision and test non-isotropic models.



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January 2013

LSST is a public-private partnership. Design and development activity is supported in part by the National Science Foundation. Additional funding comes from private gifts, grants to universities, and in-kind support at Department of Energy laboratories and other LSSTC Institutional Members.