Large Synoptic Survey Telescope

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Measuring RR Lyrae Stars Throughout the Local Group with LSST

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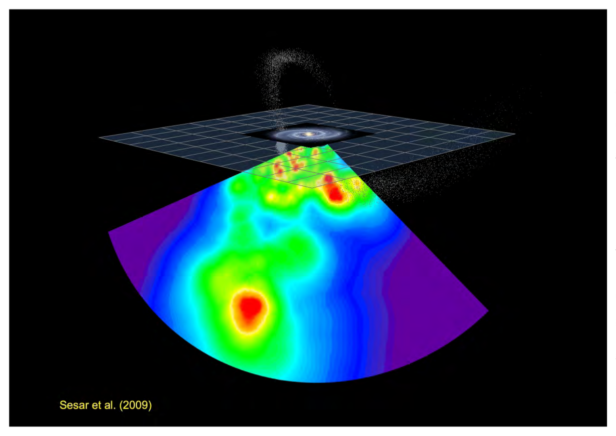
We report on a study to determine the efficiency of the Large Synoptic Survey Telescope to recover the periods and shapes of RR Lyrae light curves, and their brightnesses. We select the smoothed light curves of 40 such stars observed by the Sloan Digital Sky Survey in the "Stripe 82" region, 30 of type RRab and 10 of type RRc, that evenly sample the known period-shape relationship for these stars. We place each of these in 1007 fields across the sky, each of which represents a different realization of the LSST sampling cadence, and that sample 5 particular observing modes. A light curve simulation tool was used to sample the RR Lyrae light curves, returning each as it would have been observed by LSST, including realistic limiting magnitudes and photometric scatter. We report here the brightness, period, Fourier-shape, and template-shape recovery as a function of distance from ~ 75 kpc to ~ 2 Mpc, with survey lengths varying from one to ten years. We find that ten years of LSST data are sufficient to recover the pulsation periods with a precision exceeding 0.001% for ~ 90% of stars within ~ 380 kpc of the Sun for Universal Cadence (UC) fields, and out to ~ 760 kpc for Deep Drilling (DD) fields, with the limit for successful period recoveries extending out to ~ 1.5 Mpc. For virtually all stars that had their periods recovered, their Fourier-based light curve shape parameter phi-31 was recovered with sufficient precision to recover photometric metallicities to within 0.14 dex out to ~ 1 Mpc in both the UC and DD fields. We outline an observing strategy that will increase the efficiency of period recovery for the majority of variable phenomena likely to be observed by LSST.

Galactic Archaeology with RR Lyrae

A major objective of modern astrophysics is to understand the details of galaxy assembly and evolution. Periodic variable stars such as RR Lyrae provide a means for mapping the Galactic structure and accretion history through relating observational parameters, such as period, amplitude of pulsation and metallicity, with evolutionary parameters such as luminosity. Overdensities in RR Lyrae distributions are indicative of the galactic merger history, may reveal the presence of new dwarf galaxies, and allow the study of Local group galaxies' halos. We report the results of a study to investigate LSST's ability to recover the pulsational characteristics and brightnesses of RR Lyrae variables throughout the local group of galaxies.

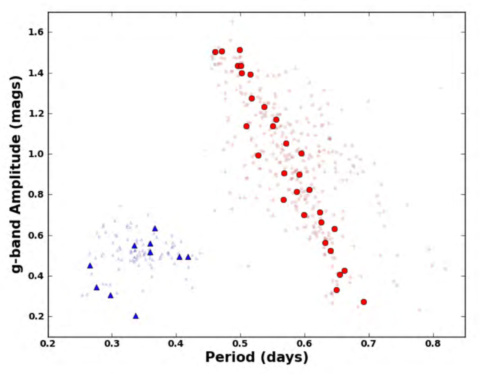


This figure from Sesar et al. (2009), which indicates RR Lyrae overdensities in red, illustrates the utility of RR Lyrae stars for identifying substructures in the Galactic halo. This data, covering ~300 square degrees to ~100 kpc, includes 483 RR Lyraes.

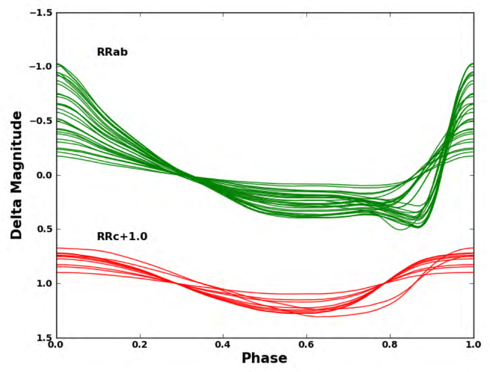
LSST will sample 18,000 square degrees on the celestial sphere and measure tens of thousands of RR Lyrae stars out to nearly 2 Mpc from the Sun.

RR Lyrae Light Curves

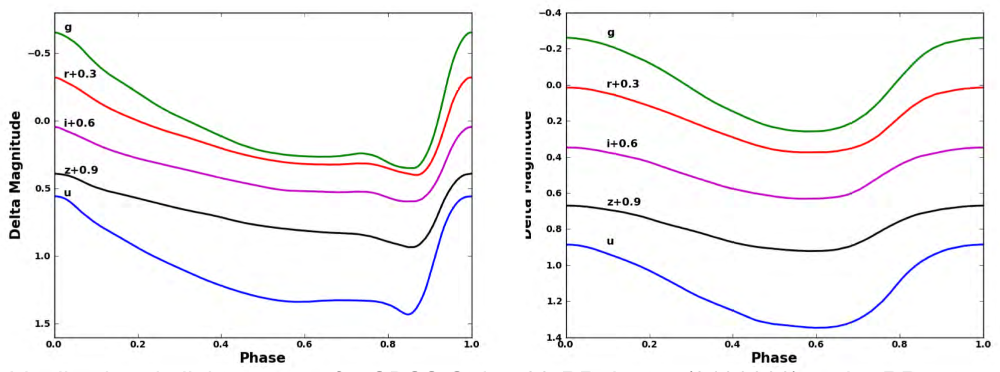
We have obtained 483 authentic RR Lyrae light curves from Sloan Digital Sky Survey (SDSS) Stripe 82 data in five photometric bands (*ugriz*), which are similar to the *ugrizY* system adopted for LSST photometry. The light curves used for our study were originally presented in Sesar et al. (2009). Below are the amplitude vs. period diagrams for the 483 stars from their survey (*grey*) and the subset of 30 RRab stars (*red*) and 10 RRc stars (*blue*) used in our simulations. These light curves uniformly sample the data set.



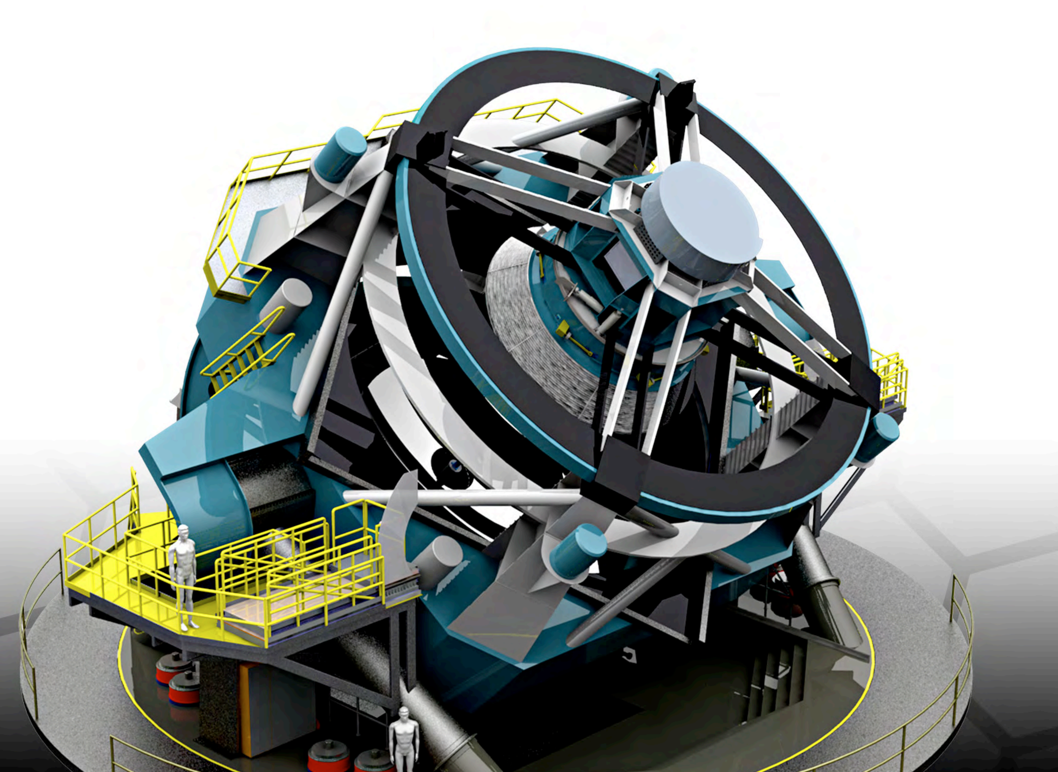
Period - Amplitude plot of 483 RR Lyrae stars as observed in SDSS Stripe 82.



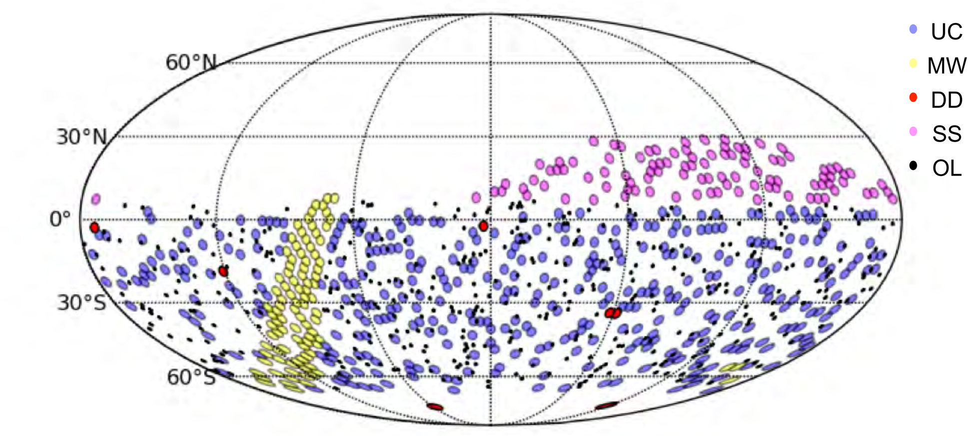
Subset of 40 RR Lyrae stars used in our study, providing a representative sample.



Idealized ugriz light curves of a SDSS Stripe 82 RRab star (3106666) and a RRc star (1141712). u(blue), g(green), r(red), i(magenta), z(black). The g-band light curve's mean magnitude has been set to zero.



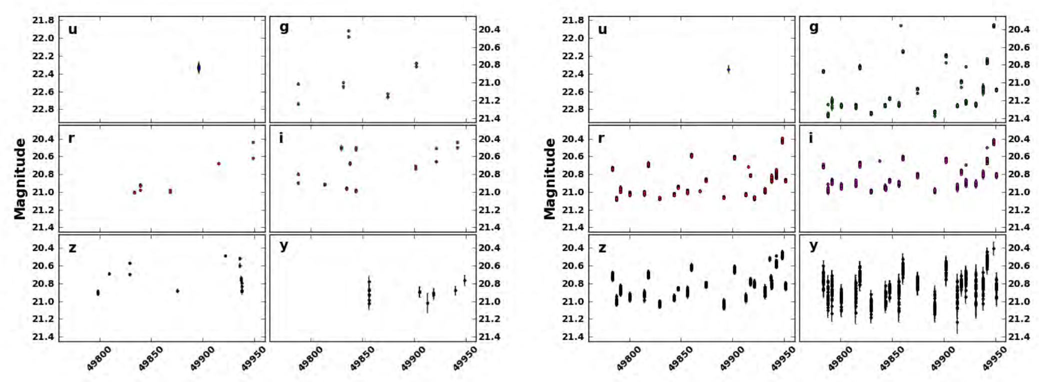
LSST Cadence Simulator



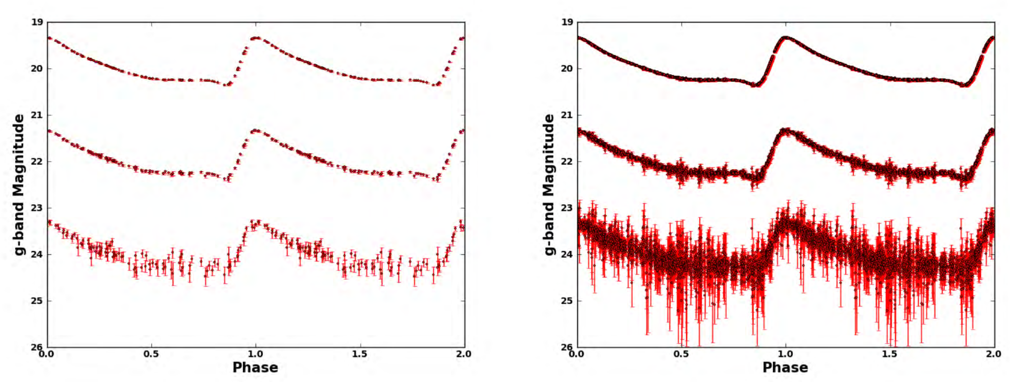
We investigate observations from 5 distinct LSST observing modes: the Universal Cadence (UC) deep–wide–fast strategy; a North Ecliptic extension optimized for Solar System (SS) observations; Milky Way (MW) observations which allocate 30 observations per filter to 103 square degrees around the Galactic center; and Deep Drilling (DD) observations which allocate 10 minutes of continuous exposure per night, distributed amongst filters on a 5–day cycle. We also examine the overlap (OL) regions between adjacent UC fields. In total we have selected 1007 field centers in which to realize each of our 40 RR Lyrae templates, such that a statistically relevant sampling of each LSST observing mode is realized.

LSST Light Curve Simulations

The light curve simulator aggregates information from the operation simulator and from the 40 idealized light curves to produce realistic observation time series of each object. Because SDSS only observed in urgiz, we use the SDSS z–band lightcurves to simulate the LSST Y–band data (i.e., z – Y = 0 at all epochs). To explore LSST's ability to recover light curve information as a function of heliocentric distance, we realize each idealized light curve used in the simulations over a range of mean *g*-band magnitudes, from 20.0 to 27.0 in steps of 0.5 magnitudes. We explore the evolution of LSST's state of knowledge of each star by exploring subsets of the ten-year simulated light curves in one year increments. In total this yields 40 light curves × 6 filters × 1007 field centers × 15 *g*-band magnitude bins × 10 sub-surveys of light curve information, for just over 36 million light curves that have gone into this study.



*200 days of simulated LSST observations of an RR Lyrae star with a magnitude offset such that the mean g-band magnitude is 21. The **left** figure shows a field sampled at the Universal Cadence (UC), while the **right** figure shows a neighboring field sampled at the Deep Drilling cadence (DD). For these particular fields, the DD cadence yields a factor of ≈ 20× more observations than in the UC fields.*

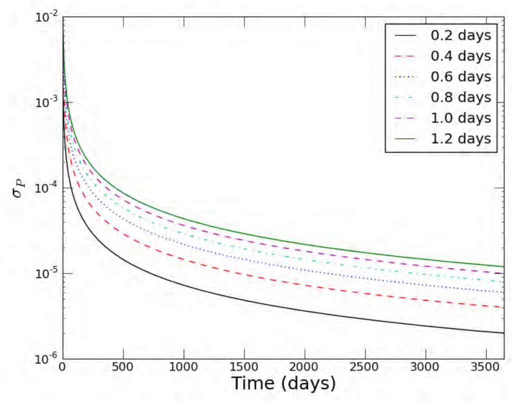


*Entire 10–year g-band light curve of the simulated LSST observations above, folded at its period of 0.594659 days. The **left** figure shows a field sampled at the Universal Cadence (UC), while the **right** figure shows a neighboring field sampled at the Deep Drilling cadence (DD). Shown are light curves for stars having mean g-band magnitudes of 20, 22, and 24.*

Defining Period Recovery

Amongst the first steps in determining a star is an RR Lyrae variable is to search for periodicity in the observed light curve. To this end we have run period--finding software on each of our 36 million simulated light curves. We used the variable span *Supersmoother* algorithm of Riemann (1994) for period estimation. *Supersmoother* is able to uncover a variety of light curve shapes since it makes no explicit assumptions about the underlying shape of the curve, only that when folded it be smooth and continuous. To ascertain whether or not *Supersmoother* recovered the known input period, we require that the product of the fractional misfit σ_P in the recovered period P_{SS} and the number of pulsational cycles $N = \Delta t / P_{in}$ be less than some fraction of a cycle $\delta\phi_{max}$ for a survey of duration Δt :

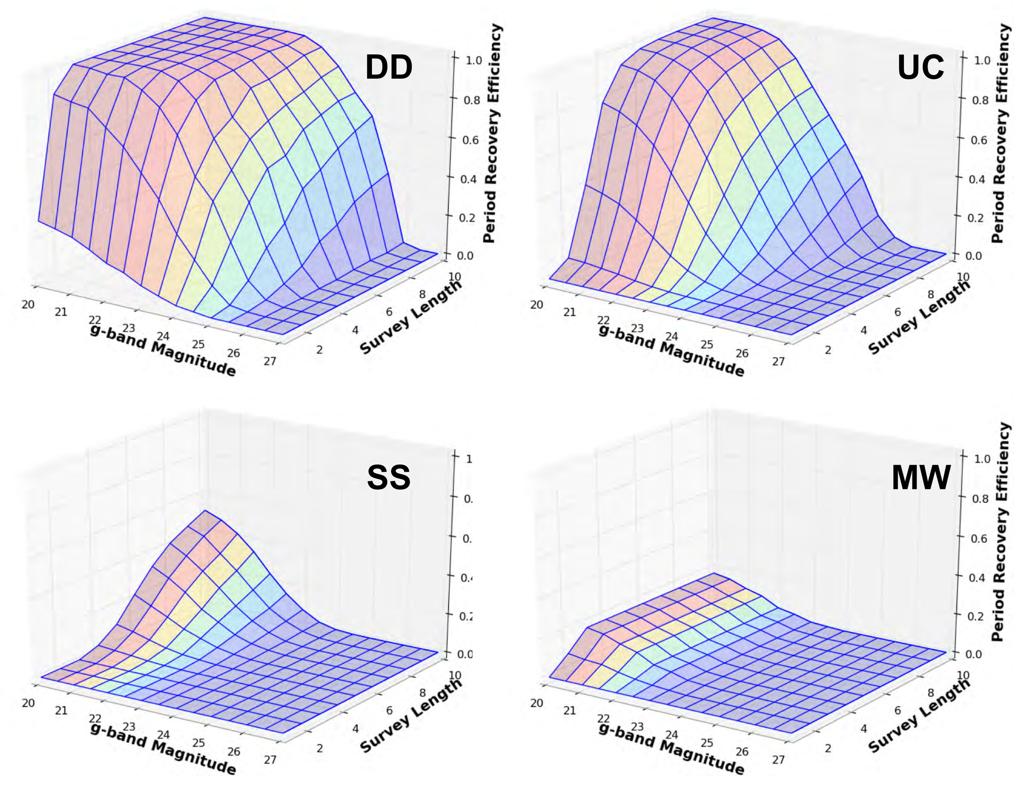
$$\frac{|P_{SS} - P_{in}|}{P_{in}^2} \leq \frac{\delta\phi_{\max}}{\Delta t} = 10^{-5}.$$



The criterion on the fractional error σ_P in the recovered period as a function of survey length and stellar period.

This criterion on σ_P is generally appropriate for stars that are variable on multiple timescales, as it provides a tighter matching criterion for shorter period stars. For a given number of observations taken over a finite window of time, shorter period stars will have gone through more oscillations, and should have a more tightly constrained period.

Period Recovery Efficiency



Shown above are the surfaces of period recovery for all stars in all filters. Note that period recovery is higher for RRab stars and in the *g*, *r* and *i* filters. Comparison of the top two surfaces shows that two years of DD data is sufficient to recover periods with the nearly same efficiency as five years of UC data. However, five years of UC data contains no more than 25% the number of field visits as two years of DD data. Apparently, the observational cadence of the UC fields is more efficient at recovering RR Lyrae periods than the cadence of the DD fields. If the DD cadence is modified to sample a greater spread in phase (> 10 mins), then the efficiency of period recovery for DD fields during the early years of the survey should increase by a few factors with no sacrifice in the ultimate coadded depth achieved.

Table 1

Magnitude limits for period recovery for a 10-year survey

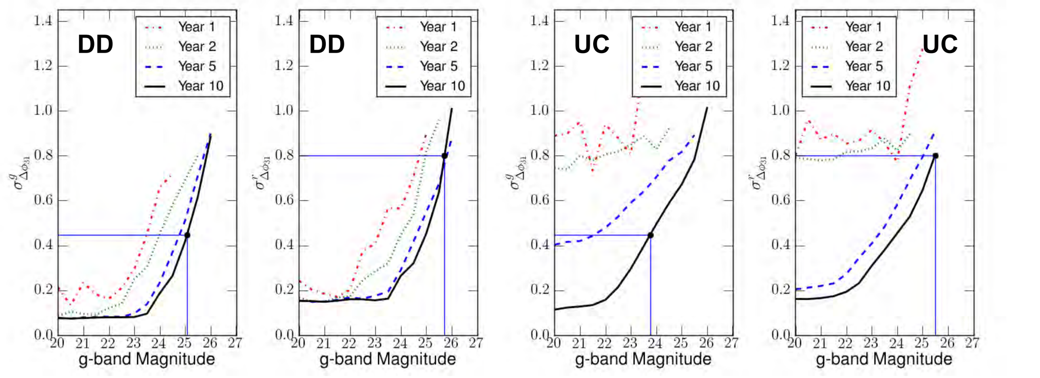
Observing mode	Recovery Efficiency 97.5%	90%	50%
DD	23.0	24.0	25.5
OL	22.0	23.0	24.5
UC	21.0	22.5	24.0
MW	–	22.0	23.0
SS	–	–	21.0

Light Curve Shape Analysis

To explore LSST's ability to recover light curve shapes via Fourier decomposition techniques, the input light curves and the folded light curve realizations generated in our simulation were all fit, via a χ^2 minimization, to a nine-term sine Fourier series of the form:

$$m_i(t) = \langle m_i \rangle + \sum_k A_k \cos\left[2\pi k f (t - t_0) + \phi_k\right].$$

where $\langle m_i \rangle$ represents the mean mag in filter *i*, A_k is the amplitude of the k^{th} harmonic, $f = 1/P$ is the frequency, and ϕ_k is the phase of the k^{th} harmonic at $t - t_0$. We compare the metallicity parameter ϕ_{31} (where $\phi_{nm} = m\phi_n - n\phi_m$) for the input light curves to that of the recovered light curves to define $\Delta\phi_{31}$. Shown below are RMS evolutions for $\Delta\phi_{31}$ histograms in DD and UC fields. The horizontal line indicates where the misfit in ϕ_{31} exceeds the uncertainty in the ϕ_{31}–[Fe/H] metallicity relations. In the *g*– and *r*–bands.



Brightness Recovery Efficiency

RR Lyrae light curve templates were spline interpolated and sampled at the phases of each light curve data realization. The templates were then fit to the simulated light curves via a χ^2 minimization. Best-fit templates were converted from magnitude units to flux units and then integrated to obtain the flux averaged magnitude (FAM). We record the frequency with which the recovered FAM is within the brightness calibration error for RR Lyraes at σ_V = 0.03 mag. Magnitudes where this occurs are recorded in Table 2.

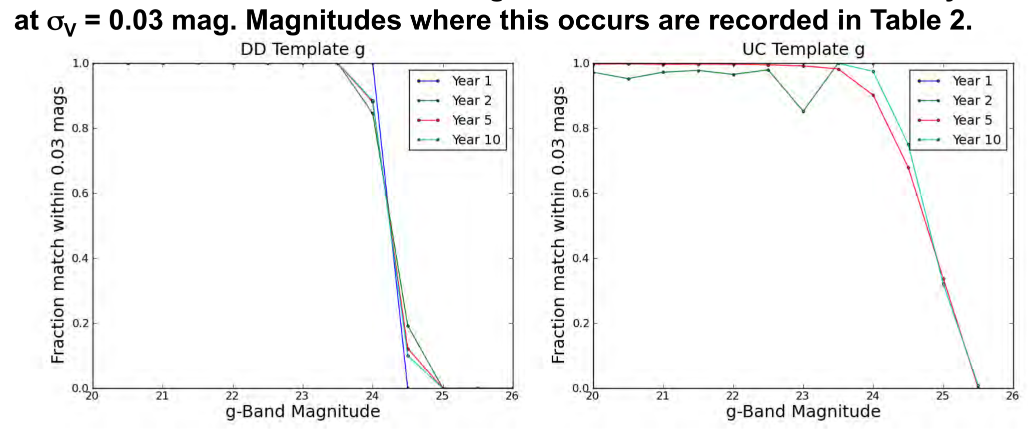


Table 2

Magnitude limits for flux recovery for a 10-year survey

Cadence	Passband *g*	*r*	*i*
DD	24.2	24.1	23.8
UC	24.7	24.5	24.1

Conclusions

The results shown here indicate that the LSST will posses unprecedented capabilities for measuring the Milky Way's history of Galactic mergers by mapping the spatial distributions and chemical compositions of stellar overdensities over a very large volume of the local group of galaxies, thus placing strong constraints on galaxy formation models; for discovering new dwarf galaxies in the Milky Way halo and beyond, addressing the "missing satellites" problem; and for mapping the halos of local group galaxies, again helping to elucidate the processes involved in galaxy formation and evolution and ΛCDM cosmology.

Acknowledgements

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