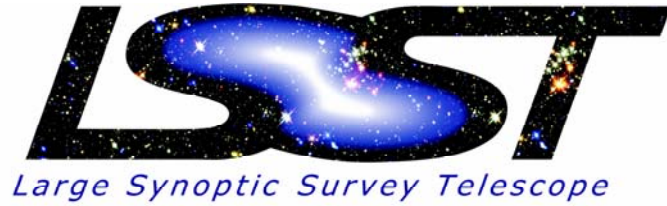


Measuring Strong Gravitational Lens Time Delays with the LSST

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The proposed Large Synoptic Survey Telescope will be the first to explore multiple dark energy probes simultaneously, including baryon acoustic oscillations, weak lensing, and strong gravitational lensing. The large data sample, covering the entire visible sky every few nights, will allow an unprecedented survey of deep supernova sources and their lensed images. The latter is a class of objects that have never been observed. Notably, LSST will measure the time delays between different strongly lensed images of the same supernova. This will provide an intriguing probe of dark matter, dark energy, and the expansion rate of the Universe. By simulating LSST observations under realistic conditions, we determined the time delay precision of multiple images from a representative strong-lensed Type Ia supernova. The output of the simulation was a set of light curves according to field and filter, which were subsequently analysed to determine the experimental time delays. We discuss the results of this analysis and its bearing on observing strategies given the predicted numbers of lensed supernovae.

Gravitational Lenses in the LSST survey

Strong gravitational lenses have traditionally been thought of as rare objects. However, the extreme surveying power of LSST forces us to reconsider the rarity of many objects. With approximately one in 1000 high redshift objects being multiply-imaged (Browne et al 2003), there will be literally millions of lensed objects (mostly galaxies) lying within the survey area. While only a fraction of these will be observable (due to the finite angular resolution and depth of the survey), LSST should still find some very useful exotic lenses, of the kind that would not be detectable with anything other than such a high-extended high-cadence system.

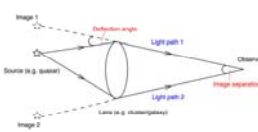


Figure 1: A gravitational lens

Gravitational Lens Time Delays

Strong lensing involves multiple imaging of objects behind the lens (figure 1). The positions of the images are determined by (and provide information about) the lens mass distribution. The relative arrival times of photons in the images are also dependent on the mass distribution: if the source is variable, the time delays between the variations in each image can be measured. With the lens mass constrained by the image positions and other observables, the time delays can be predicted, in units of H_0^{-1} days, where H_0 is Hubble's constant. Comparing the predicted delays with the measured time delays gives a value for H_0 . Conversely, if the Hubble constant is assumed to be known from other measurements, then the time delays provide valuable information on the mass distribution in the lensing galaxy.

Most strong lenses in the Universe are massive elliptical galaxies lensing high redshift galaxies – these systems typically have time delays of a few months. For the time delay to be observable the source has to be variable. Therefore, monitoring efforts up to this point have concentrated on observations of lensed quasars, with monitoring programs lasting several years and with cadences ranging between several days and 2 weeks. Time delays have been measured in over 10 systems, resulting from monitoring programs at radio (e.g., Fassnacht et al. 1999,2002, Biggs et al. 1999) and optical (e.g., Schechter et al. 1997, Burud et al. 2002a,b; Kochanek et al. 2005). Here we investigate the possibility of using a completely new population for lens time-delay measurements: *gravitationally-lensed supernovae*.

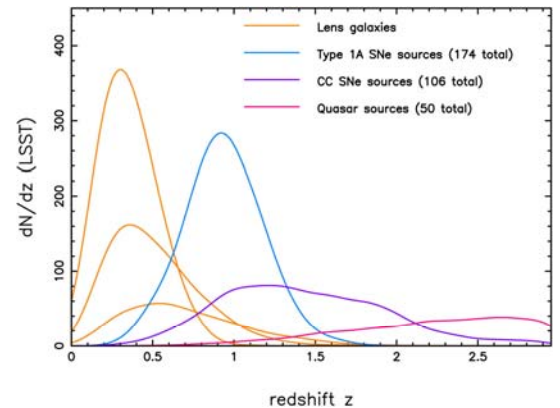


Figure 2: Redshift distributions of measurable lensed supernovae in the LSST survey area. The middle of the two lens-galaxy curves corresponds to the lensed core-collapse supernovae, while the lower curve corresponds to the quasar lenses. These numbers were calculated using the SDSS massive galaxy number density (Sheft et al 2003), and source populations from the 2dF quasar counts (Croom et al 2004) and the SNOG simulation package (Goobar et al 2002). For this plot we assume consistent 0.7 arcsec seeing, a magnitude limit of 23 for each measurement, and a 10-year 20000 square degree survey, BUT with 50% visibility at any one time, and a completeness of 15% reflecting the fraction of data expected to be useful for time delay measurement.

Time Delay Measurability

Supernovae would make much better sources for measuring lens time delays: their light curves show obvious, template-following peaks. These peaks last for around a month (more when observed at high redshift due to time dilation), requiring a monitoring system with a cadence of 1-2 weeks. LSST is such a system. Figure 2 shows that, over a ten year period, and in a given area of sky to LSST depth, more supernovae occur than there are quasars. From this figure we may anticipate observing, and extracting lens time delays from, a few hundred lensed supernova systems; until LSST comes on-line there may not a single lensed supernova observed.

The curves in figure 2 are sensitive to the details of the LSST observing program. We investigated this by using the LSST cadence simulator (figure 3) to place a fiducial quadruple-image system in each of 2000 LSST fields, and tabulated the dates of observation, seeing, and sky brightness for each visit for a one year period. We then used this information to produce simulated postage stamp images of the lens system, one 30 second "exposure" for each visit (figure 4). For each field we then constructed an "observed light curve," detecting the SN in each image and plotting the measured flux with time (figure 5). From the light curves we estimated the time delay between three pairs of images, estimating the light curve peaks with a flux-weighted mean and then taking differences between images. In order to estimate the accuracy with which the time delays could be measured, we plot histograms of the fractional time delay error (figure 6).

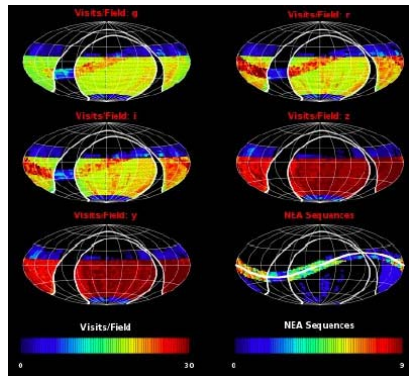


Figure 3: Illustration of example sky coverage produced by the LSST cadence simulator. Typically more of the useful images fall in the r-filter, which is preferentially used in good seeing conditions for the weak lensing program.

