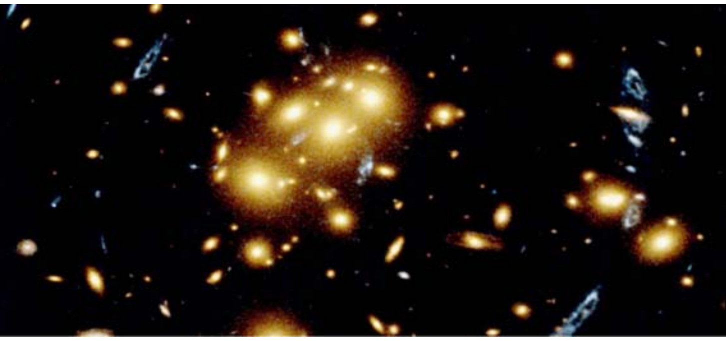
Large Synoptic Survey Telescope



Gravitationally Lensed Quasars - Lessons from SDSS and Predictions for LSST

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The SDSS survey is uncovering many gravitationally lensed quasars and demonstrating the usefulness of large-scale optical surveys for lens statistics. In the SDSS, lensed quasars are surveyed by searching "extended" quasars for small-splitting lenses, or by comparing colors of stellar objects nearby quasars if lensed images are well resolved. Although LSST data have no spectroscopic information, its multi-epoch multiwavelength imaging observation makes it possible to conduct an efficient search of lensed quasars by making use of their colors and time variability. We will discuss the prospect for finding lensed quasars from LSST and for determining cosmological parameters.

Gravitationally Lensed Quasars

Multiple quasars lensed by a foreground massive object (Fig. 1) serves as a unique probe of our Universe. For instance, the well-understood underlying physics makes is a useful probe of cosmology. In addition, because of its gravitational nature of the phenomena it is thought as an ideal tool to study the distribution of dark matter. Although lensed quasars are rare phenomena, have been discovered only ~100 systems to date, future large surveys like Large Synoptic Survey Telescope (LSST) will discover much more lensed quasar systems.

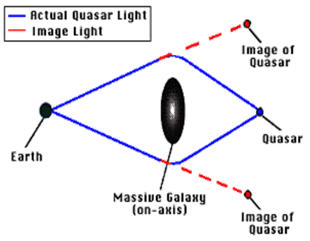


Fig. 1: Configuration of a strongly lensed quasar system. The light path of background quasar (blue dot) is deflected by a foreground massive galaxy, causing multiple images of the quasar at red points. The different paths result in time delay between arrival times of signals. Taken from http://imagine.gscf.nasa.gov/

Quasar Lens Search in the SDSS

The Sloan Digital Sky Survey (SDSS) is a large-scale optical survey conducting both imaging and spectroscopy. A lensed quasar survey with the SDSS data (Oguri et al. 2006, AJ, 132, 999) demonstrates that wide field optical survey is an efficient way to locate many lensed quasars. In the SDSS, lens candidates are selected in two complementary ways: One is morphological selection which looks for "extended" quasars as small-separation lens candidates. The other is color selection in which colors of two resolved objects are compared to test their lensing interpretation. The imaging and spectroscopic follow-up observations are conducted with many other telescopes to identify genuine lens systems. Using the technique SDSS has already uncovered ~20 new strongly lensed quasars (Fig. 2). The survey is still ongoing, and at the final stage a clean sample of ~40 lensed quasars will be constructed from the SDSS data.

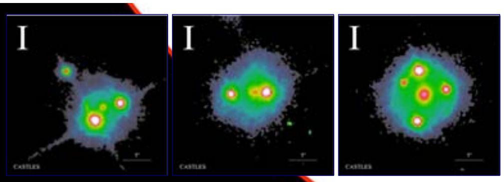


Fig. 2: A few examples of HST images of lensed quasars newly discovered from the SDSS. Taken from the CASTLES site (http://cfa-www.harvard.edu/castles/)

LSST versus SDSS

The LSST is a next-generation optical survey in which we expect to find much more lensed quasars than SDSS. The right table compares LSST and SDSS to show how different these two surveys are. First of all, LSST images are deeper and has higher resolution than SDSS images. The high spatial resolution is essential in secure identification of lensed quasars since their typical image separation of 1" is similar to the seeing size of ground based imaging (see Fig. 3). More important difference is the survey styles. The SDSS conducts extensive spectroscopic observations, whereas LSST is an imaging-only survey. However, very unique feature of LSST is rapid, repeated scan imaging that opens up time domain science. Indeed, the time domain is invaluable to lensed quasar search, because (i) it allows a new efficient way to locate lensed quasars by making use of strong time variability of quasars (Pindor 2005, ApJ, 626, 649; Kochanek et al. 2006, ApJ, 637, L73), and (ii) the frequent image sampling provides a large sample of time delays between multiple images (Fig. 4).

LSST		SDSS
20,000deg^2	sky coverage	8,000deg^2
ugrizY	filters	ugriz
0.2"/pixel	pixel scale	0.4"/pixel
~0.7"	typical seeing	~1.2"
i=24.0 (1 visit)	mag limit	i=21.2
repeated scan imaging	survey style	single image +spec

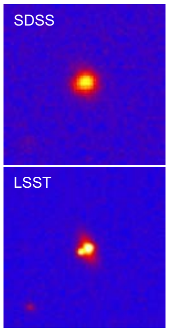


Fig.3: The SDSS image of double lens SDSS J1332+0347 (Morokuma et al. astro-ph/0609695) and corresponding image that would be taken at LSST (in practice the "LSST" image was taken with Suprime-cam at Subaru). Two lensed quasar components and a lensing galaxy is seen much more clearly in the LSST image.

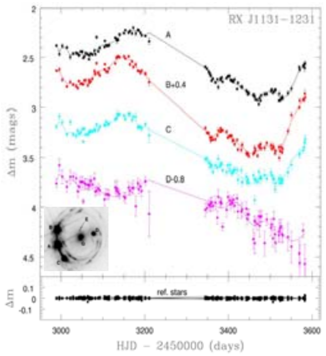


Fig. 4: Lightcurve of quadruple lens RXJ1131-12 from optical monitoring (Morgan et al. astro-ph/0605321). The photometric accuracy and cadence are similar to those of LSST, thus we expect to obtain similar lightcurves (and hence time delays) for lensed quasars discovered in LSST.

Lensed Quasars in LSST

Here we predict the number distribution of lensed quasars in LSST. We assume Singular Isothermal Ellipsoid (SIE) for lensing galaxies. The velocity function of Choi et al. (astro-ph/0611607) is adopted. The quasar luminosity function is mostly based on Richards et al. (2006, AJ, 131, 2766). We also include external shear. In computing magnification bias, we use the magnification factor of the third brightest image (the fainter one for double lenses), assuming that we identify lenses using time variability. The survey area is set to 15,000deg^2. Results are shown in Figs. 5-7.

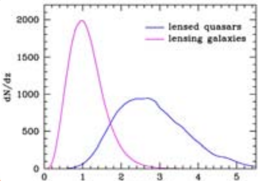


Fig. 5: The redshift distribution of lensed quasars and lensing galaxies. The image separation between 0.5" and 3" and magnitude brighter than i=24 are considered.

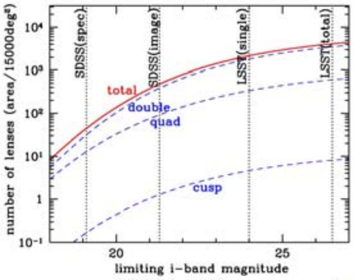


Fig. 6: The number of lensed quasars as a function of the limiting magnitude. The image separation is between 0.5" and 3". Numbers of double, quad, and naked cusp lenses are shown separately. Note that LSST lensed quasars are dominated by double lenses mostly because of smaller magnification bias.

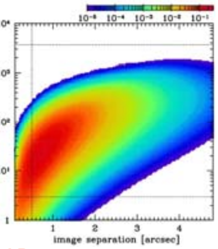


Fig. 7: Contour plot of the distribution of image separation and time delay, $d^2n/d\theta d\log\Delta t$. Dotted lines indicate rough LSST limits of lens selection (>0.5") and time delay measurement (3days<Δt<10years). This Figure suggests that we will indeed be able to measure time delays for most of lensed quasar systems discovered in LSST.

Constraints on Cosmological Parameters

From a large homogeneous sample of time delays, we can constrain not only the Hubble constant but also dark energy property. In Fig. 8, we show expected level of constraints on cosmological parameters from ~1,200 double lenses with i<23. We assume that photometric redshifts are used, but also consider the case that spectroscopic redshifts are obtained from follow-up observations. The spectral information does not drastically improve the constraints, indicating that photometric redshifts are reasonably good for this purpose.

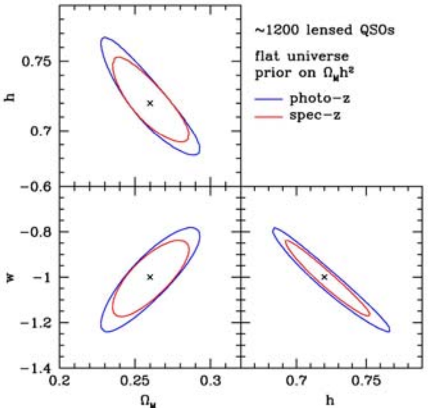
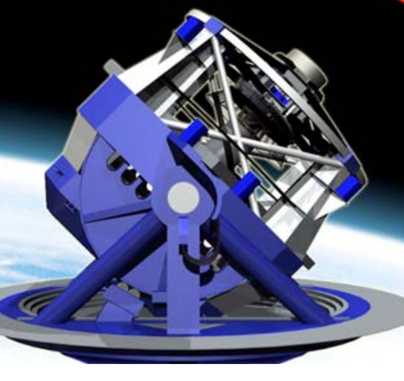


Fig. 8: Expected 1-σ constraints in projected spaces from ~1,200 double lenses. For photometric redshifts, we assume errors of 0.1 for quasars and 0.05(1+z) for lensing galaxies. The 20% uncertainty of lens potentials is considered (Oguri, astro-ph/0609694). The time delay measurement error is assumed to be 3 days. We include a conservative prior $\Delta(\Omega_M h^2)=0.005$ that can easily be obtained from CMB anisotropy or baryon acoustic oscillation measurements. Note that if we fix Ω_M and w we can obtain very strong constraint on h, $\Delta h=0.005$.



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