Large Synoptic Survey Telescope

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LSST Strong Lensing: Galaxies and Their Nuclei Under A Gravitational Microscope

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LSST will open a new era in the monitoring of gravitationally lensed quasars. By providing well-sampled multicolor light curves, LSST will allow us to cleanly separate microlensing by stars from macro/milli-lensing by dark matter halos and substructure in a large sample of strong lenses. We discuss how chromatic microlensing light curves from LSST will let us disentangle the stellar and dark matter densities in lens galaxies, and also zoom in to study the wavelength-dependent structure of quasar accretion disks. We also discuss the potential of LSST to revolutionize the study of millilensing by CDM substructure by providing not only flux ratios but also time delays for a large sample of lenses. Finally, we discuss the exciting prospect of having a lens sample large enough to examine how small-scale structure in galaxies and their nuclei evolves over a significant fraction of the age of the universe.

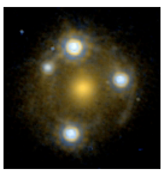


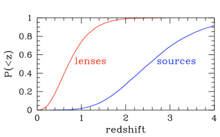
Fig. 1. The gravitational lens SDSS J0924+0219. A quasar at redshift z_s=1.52 is lensed into four images by a galaxy at z_l=0.39, which lie about 0.9" from the center of the galaxy. Microlensing demagnifies the image at the top left by a factor >10, relative to a smooth mass distribution. (From Keeton et al. 2006.)

I. Multiscale Gravitational Lensing

Gravitationally lensed images of distant quasars contain a wealth of information about small-scale structure in both the lens galaxy and the source quasar. Key (angular) scales in the lens galaxy are:

- ***Macrolensing*** (θ~1") by the global mass distribution sets the overall positions, flux ratios, and time delays of the images.
- ***Millilensing*** (θ~1 mas) by dark matter substructure perturbs the fluxes by tens of percent or more, the positions by several to tens of mas, and the time delays by hours to days.
- ***Microlensing*** (θ~1 μas) by stars sweeping across the images causes the fluxes to vary on scales of months to years (Fig. 2).

Additional scales are set by the size of the source. Broad-band optical observations measure light from the quasar accretion disk, which can be comparable to the Einstein radius of a star in the lens galaxy. Thus finite source effects can make microlensing chromatic.



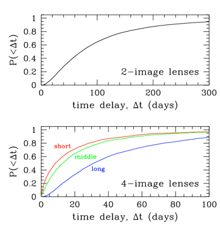
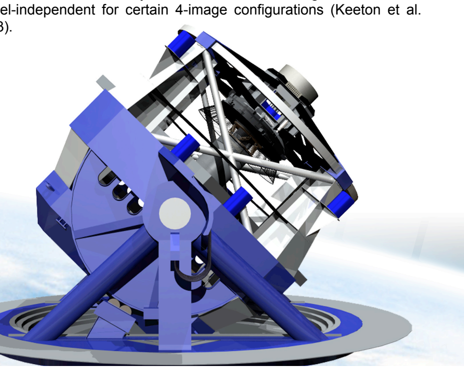


Fig. 3 *(above)*. Predicted cumulative redshift distributions for lens galaxies (red) and source quasars (blue) in the LSST strong lens sample.

Fig. 4 *(right)*. Predicted cumulative time delay distributions for 2-image and 4-image lenses. Each 4-image lens has three independent time delays.

II. LSST Strong Lens Data

LSST is expected to discover a myriad of lensed quasars and measure well-sampled, 6-band light curves for ~4000 of them. Time delays between images can be measured by cross-correlating light curves to identify the same features offset in time. LSST's planned cadences should make it possible to determine the time delays of most 2-image lenses, and multiple time delays in many 4-image lenses (Fig. 4). Microlensing is revealed by uncorrelated (and possibly chromatic) variations in different images (e.g., Lewis et al. 1998). Millilensing can be identified by deviations from smooth model predictions; while this analysis often involves modeling, it can be made model-independent for certain 4-image configurations (Keeton et al. 2003).



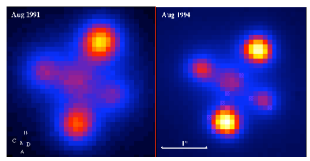


Fig. 2. Microlensing-induced variability in the lens Q2237+0305. (Lewis, Irwin, et al., http://apod.nasa.gov/apod/ap961215.html)

III. Dissecting Quasar Accretion Disks

Microlensing effectively boosts the resolution of a telescope to micro-arcsecond scales. Individual stars in a lens galaxy cause the lensing magnification to vary over μas scales. As the quasar and stars move, the accretion disk feels the variable magnification. The variability time scale is typically months to years, although it can be more rapid when the source crosses one of the lensing caustics (the bright bands in Fig. 5). The variability amplitude depends on the quasar size relative to the Einstein radius of a star (projected into the source plane),

$$R_E \sim 5\times10^{16}\ \mathrm{cm}\times\left(\frac{m}{M_\odot}\right)^{1/2}$$

for typical redshifts. According to thin accretion disk theory (Shakura & Sunyaev 1973), the effective size of the thermal emission region at wavelength λ is

$$R_\lambda \approx 9.7\times10^{15}\ \mathrm{cm}\times\left(\frac{\lambda}{\mu\mathrm{m}}\right)^{4/3}\left(\frac{M_{BH}}{10^9\,M_\odot}\right)^{2/3}\left(\frac{L}{\eta L_E}\right)^{1/3}$$

where η is the accretion efficiency. By comparing the variability amplitudes at different wavelengths, we can determine the relative source sizes and test the predicted wavelength scaling. With black hole masses estimated independently from emission line widths, we can also test the mass scaling. These methods are in use today (e.g., Kochanek et al. 2006), but the expense of dedicated monitoring has limited sample sizes to a few. *LSST is ideal for microlensing studies of quasar accretion disks because it will provide well-sample, 6-color light curves of ~4000 lensed quasars.*

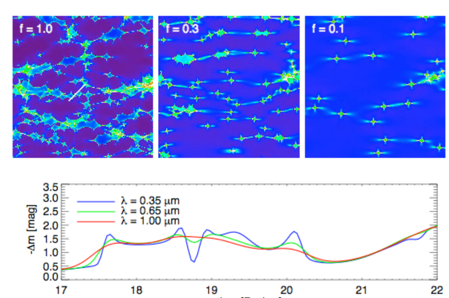


Fig. 5. *(Top)* Sample microlensing magnification maps. The maps are 30 R_E ~ 10^{18} cm on a side. The panels have the same total surface mass density but a different fraction *f* of mass in stars. *(Bottom)* Examples of predicted light curves produced when the source moves along the trajectory shown in the top left panel. The different line types denote different wavelengths and hence source sizes.

References

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IV. Finding Smooth and Lumpy Dark Matter

Microlensing is sensitive to the mix of stars and dark matter at the positions of the images (Fig. 5); it therefore provides a unique tool for measuring local densities (as opposed to integrated masses) of dark matter in distant galaxies. The large sample of microlensing light curves provided by LSST will make it possible to measure stellar and dark matter densities as a function of both galactic radius and redshift.

Lensed images are also sensitive to the substructure predicted to be abundant in Cold Dark Matter halos. CDM substructure is detected not through variability (the time scales are too long), but rather through patterns of image positions, flux ratios, and time delays that cannot be produced by any smooth mass distribution. Flux ratio "anomalies" consistent with CDM substructure have already been observed in a small sample of 4-image lenses; they provide the only existing measurement of the amount of substructure in galaxies outside the Local Group (Dalal & Kochanek 2002). LSST will increase the sample by some two orders of magnitude.

LSST will also open the door to using lens time delays as a new probe of CDM substructure (Fig. 6). Unlike flux ratios, time delays probe the mass function of CDM subhalos, which is sensitive to the physical properties of the dark matter particle (Keeton & Moustakas 2008). The number of LSST lenses with time delays accurate enough to constrain substructure will depend on the cadence distribution and remains to be determined. It is clear, though, that LSST will provide the first large sample of time delays, which will enable qualitatively new substructure constraints that provide indirect but important astrophysical evidence about the nature of dark matter.

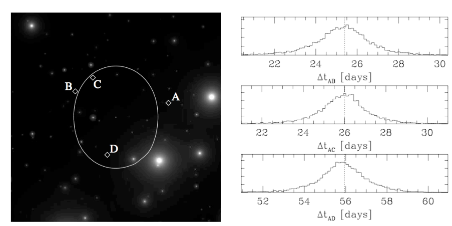

Fig. 6 *(Left)* Sample mass map of CDM substructure from semi-analytic models by Zentner & Bullock (2003). (The smooth halo is not shown.) The points indicate sample lensed images. *(Right)* Histograms of the time delays between the images, for 10^4 Monte Carlo simulations of the substructure. The dotted lines show what the time delays would be if all the mass were smoothly distributed.

V. The Future of Multiscale Lensing With LSST

The lens galaxies and source quasars discovered by LSST will span a wide range of redshift, and hence cosmic time (Fig. 3). The sample will be large enough that we can search for evolution in quasar structure, dark matter densities, and CDM substructure. It will be interesting to see whether evolution in the quasar luminosity function (e.g., Hasinger et al. 2005) is accompanied by evolution in the size distribution. It will also be interesting to see whether the amount of CDM substructure decreases or increases in redshift; that will reveal whether the accretion of new subhalos or the tidal disruption of old subhalos drives the abundance of substructure. Also, the cosmic evolution of substructure is a key prediction of dark matter theories that is not tested any other way. Thanks to its ability to both discover and monitor many lensed quasars, LSST will be an invaluable tool for studying the evolution of small-scale structure in galaxies and quasars.

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