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COSMOLOGY WITH GRAVITATIONAL LENSES

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RESUMEN

Las lentes gravitatorias rinden altísimas tasas de beneficio a las inversiones observacionales. Considerando su baja incidencia, su impacto hasta hoy en nuestro conocimiento del universo es muy importante. En el límite de campos débiles, los estudios de lentes utilizan conocimiento físico bien establecido, y por ello nos ofrecen un camino claro para estudiar toda una serie de problemas críticos de la astrofísica. Algunos ejemplos son la importancia de la materia oscura y la densidad, edad y tamaño del universo. Presento avances recientes en las aplicaciones a la cosmología de las lentes gravitatorias, particularlmente en cuanto a la estimación de la constante de Hubble utilizando el efecto "fuerte" de lentes en el ámbito de los cuasares. Describo nuestras mediciones recientes de retrasos temporales para las imágenes de SDSS J1004+4112, y discuto las perspectivas para el futuro, utilizando telescopios sinópticos que se planean construir o están en construcción.

ABSTRACT

Gravitational lenses yield a very high rate of return on observational investment. Given their scarcity, their impact on our knowledge of the universe is very significant. In the weak-field limit, lensing studies are based on well-established physics and thus offer a straightforward approach to pursue many currently pressing problems of astrophysics. Examples of these are the significance of dark matter and the density, age and size of the universe. I present recent developments in cosmological applications of gravitational lenses, regarding estimates of the Hubble constant using strong lensing of quasars. I describe our recent measurements of time delays for the images of SDSS J1004+4112, and discuss prospects for the future utilizing synoptic telescopes, planned and under construction.

Key Words: cosmology — gravitational lensing — observations

1. INTRODUCTION

Gravitational lens systems (hereafter GLS) consist of a source and the lens itself, which deflects the light of the source and forms distorted images; Figure 1 is a sketch of a typical configuration. GLS sometimes form multiple images of a source, such as those shown in Figure 2. I only consider the gravitational weak-field limit, where deflections are always $\ll 1$ radian, or a few arcsec. In this l imit, the deflection is achromatic (with observational caveats, e.g., from extinction or from the variation of the sizes of sources with wavelength). Thus, a diagnostic property of GLS is that the images are unchanging with the wavelengths of observations. For example, lensed multiple images of quasars have very similar flux ratios in different wavebands (Figure 2) and their spectra yield a common redshift (Figure 3). The examples in these and in Figures 4 and 5 show cases of "strong" gravitational lensing with different morphologies; the typical scale for separation between distinct images of a quasar is a few arcsec and the lens is most frequently a massive elliptical galaxy.

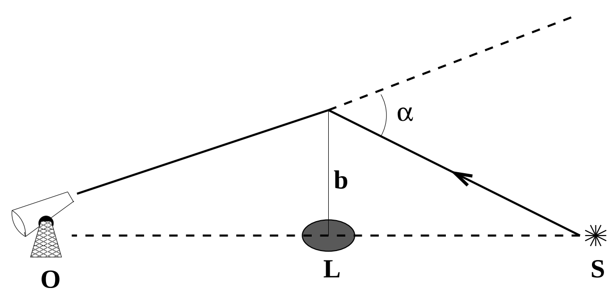

Fig. 1. The sketch shows light emitted, deflected and detected, with the observer and her telescope at O, the lens at L and the source at S. The impact parameter is b; the corresponding deflection angle is α ($\ll 1$ radian, greatly exaggerated here).

In a different occurrence of strong lensing, the effect yields distorted (at times multiple) images of distant galaxies, varying from "arclets" (slightly distorted) to "giant arcs" (greatly sheared), produced by intervening clusters of galaxies. There are two additional classes of gravitational lensing: "weak" lensing, where the strength of the lensing is insufficient to form multiple images and the effect is only measurable statistically and "microlensing" where un-

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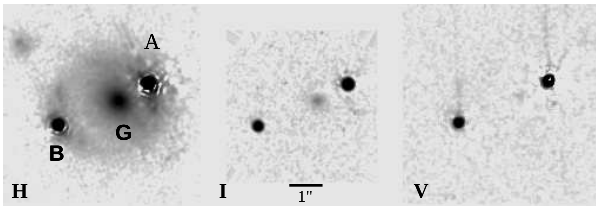

Fig. 2. HST H, I and V filter views of HE1104-1805, a double system. The lens galaxy is G, the images A and B. North (East) is at the top (left). Here, we fitted a photometric model, subtracted the best-fit models for the quasar images, and re-added them as gaussians with the same width as the original PSFs. This procedure removes artifacts due to the diffraction pattern of the HST PSFs.

resolved (at the micro-arcsec level) sub-images are formed and the detectable results are large, rapid changes in detected fluxes.

The gravitational potential fluctuations of weak lenses cause modest distortions in the shapes of background sources. By measuring such distortions, one can determine the amplitude of density fluctuations as a function of cosmic distance. Tomographic surveys that include the radial cosmic coordinate yield 3D information; otherwise, one determines 2D variations, where the radial coordinate is integrated out. The current weak-lensing measurements are degenerate: measurements may be consistent with small (large) fluctuations in a high (low) density universe. The current weak-lensing determination is $\Omega_m \approx 0.3$ with a 10% error (Wittman et al. 2003).

Microlensing forms multiple images, but with very small separations, 10^{-6}to10^{-3} arcsec, usually unresolvable. But one can easily detect the corresponding large increases in the total brightness of the lensed source. Many interesting results arose from the pioneering work of several projects, the Massive Compact Halo Object (MACHO), Expérience de Recherche d'Objets Sombres (EROS) and Optical Gravitational Lens Experiment (OGLE) collaborations and the world-wide collaboration Probing Lensing Anomalies NETwork (PLANET). These groups monitored stars in the LMC and attempted to find rapid brightness (thus, lens magnification) variations due to compact dark matter in the galactic halo (e.g., Evans 2003). MACHO concluded that about 20% of the Milky Way halo is in compact objects of about 0.5 solar masses. Such a high mass content exceeds the total mass of the known stars. EROS found fewer microlensing events than MACHO, and set an upper limit of 25% for the compact dark matter content of the halo. Thus, only a small

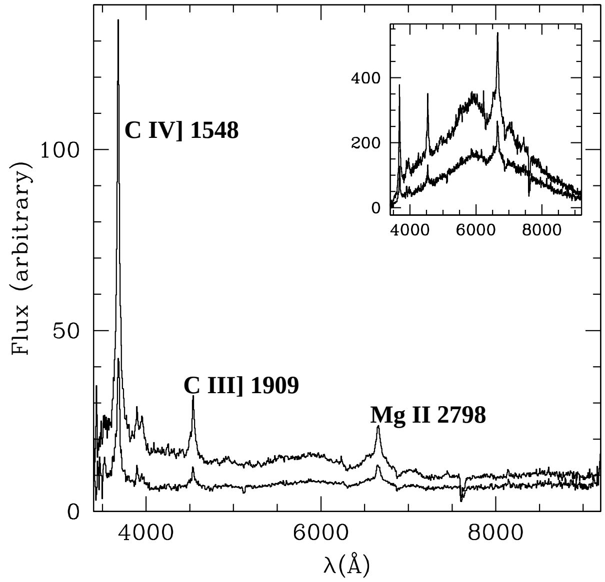

Fig. 3. Spectra of the 2 images of the double system SBS0909+532, with redshift $z_s \sim 1.38$. The lens galaxy is at $z_l \sim 0.8$. The inset shows the spectra before corrections for instrumental and systematic effects (Motta et al. 2002). A useful feature of quasars as lensed sources is that their spectra have multiple broad emission lines as in this case.

fraction of the dark matter in the halo of the Milky Way appears to consist of MACHOs: dark matter is of a still undiscovered type.

In the following, I concentrate on applications of observations of strong GLS to the study of cosmology. I first summarize CASTLES (CfA-Arizona Space Telescope Lens Survey) and then discuss our monitoring over the past 4 years of the SDSS J1004+4112 lens system and our results so far. I conclude with the future of surveys that are or will in the next several years be poised to make substantial contributions to these studies. In this paper, I assume a flat universe within the concordance cosmology.

2. CASTLES: A LENSED QUASAR SAMPLE

As the characteristic size of galaxy-scale lenses is $\Delta\theta \sim 1$ arcsec, precision photometric studies of the lensing galaxies and of lensed quasar host galaxies are only practical with HST. HST also provides the best possible refinement of astrometry at optical and infrared wavelengths for components of GLS.

The CASTLES project (CfA/Arizona Space Telescope LEns Survey[2]) is a non-proprietary survey

[2]See cfa-www.harvard.edu/castles.

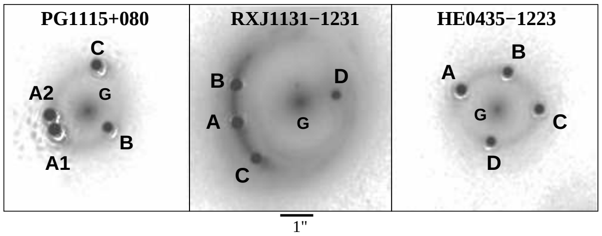

Fig. 4. CASTLES (see the text) HST NICMOS H-band images of 3 quadruple GLS. The different configurations in the 3 panels arise from the positioning of the source relative to the caustic curves generated by the lens (e.g., Schneider, Kochanek, & Wambsganss 2006). We used the same procedure as in Figure 2 to remove PSF artifacts.

of known galaxy-mass GLS using the Hubble Space Telescope (HST) with a standard set of filters. A fundamental goal of CASTLES is to obtain accurate astrometric measurements and photometry of lens galaxies and lensed images to refine lens models, particularly for systems where a time delay may provide a direct measurement of $H_\circ$. Other significant CASTLES goals are direct estimates of the mass-to-light ratio M/L of lens galaxies up to $z \sim 1$, a comparison of the dark matter and stellar light distributions in the lens galaxies, measurements of the properties of the interstellar medium in distant galaxies using differential extinction between the lensed images, identification of as yet undetected lens galaxies in known multiple-image systems, understanding the environments of lens galaxies.

CASTLES currently includes $\sim$ 100 small-separation ($\Delta\theta \leq 15$ arcsec) GLS. The GLS in CASTLES were found as a product of optical quasar surveys, radio lens surveys and serendipity (e.g., see Kochanek 1993). In all cases, there is a dominant lens galaxy which may be a member of a group or small cluster. The heterogeneity of the overall sample is important for some questions (e.g., the separation distribution), but relatively unimportant for others (e.g., the evolution of the lens galaxies). We observed our targets in the near infrared (principally the H band, but in a few cases, J and K) with the NICMOS camera NIC2. The infrared observations are complemented by WFPC2 imaging in the optical I and V bands to obtain uniform multi-color photometry of the systems. In recent HST cycles, we continued to use NIC2 and we also used ACS/WFC (Advanced Camera for Surveys) with the wide-field camera and V and I filters. The ACS failure in January 2007 prevented continuation of the survey until possibly the next HST cycle.

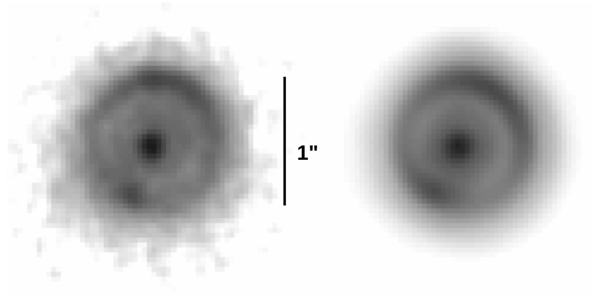

Fig. 5. Left panel: CASTLES HST NICMOS image of the complete Einstein-ring BLS B1938+666. Right panel: a photometric model including an elliptical lens galaxy and a lensed extended source to produce the ring.

CASTLES observations have yielded studies of dark matter (Rusin et al. 2003) and of the interstellar medium in lens galaxies at redshifts up to $z \sim 1$ (Falco et al. 1999), as well as the properties of lensed quasar hosts at $z > 1$ (Peng et al. 2006). Gravitational lensing enables such studies at high redshifts.

3. TIME DELAY MEASUREMENTS

Estimating $H_\circ$ has been a challenge since the 1920s. The classic approach is to build a cosmic distance ladder. One uses nearby celestial objects, for which distances can be measured relatively easily, to calibrate the distances to objects farther away. In that fashion, we can bootstrap to distances to far-off objects that move predominantly with the Hubble flow (i.e., for which the cosmic expansion velocity is much larger than their peculiar velocities). Unfortunately, we have a limited understanding of the underlying physics of many of the objects that are used to construct the distance ladder. Therefore, the empirical corrections that need to be applied to observations can hide biases that limit the reliability of the results.

GLS yield accurate, independent estimates of $H_\circ$ that bypass the distance ladder. The concept (Refsdal 1964), is to monitor multiple images created by a strong lens such as those in Figure 4. The travel times associated with the different images formed by such lenses differ from the single travel time in the absence of a lens. The differences in the geometrical pathlength for each image and in the gravitational potential experienced by deflected light rays account for the differences in these travel times, or time delays Δt. Delays range from days to years, and are inversely proportional to $H_\circ$. One can conduct lensing measurements on relatively nearby sources ($z < 2$, say), which allow one to determine a value

TABLE 1

MEASURED TIME DELAYS[a]

Lens Name	$N_{\rm im}$	z_s	z_l	im. pair	Δt [days]	im. pair	Δt [days]
B0218+357	2	0.944	0.685	AB	10.5 ± 0.2		
HE0435−1223	4	1.689	0.455	AD	$14.4^{+0.9}_{-0.8}$	AB	$8.0^{+0.8}_{-0.7}$
				AC	$2.1^{+0.7}_{-0.8}$	BD	6.4 ± 0.8
				CD	12.3 ± 0.8	BC	5.9 ± 0.8
RXJ0911+0551	4	2.800	0.769	A1B	143.0 ± 6.0	A2B	149.0 ± 8.0
				A3B	154.0 ± 16.0		
SBS0909+532	2	1.377	0.830	AB	$45.0^{+5.5}_{-0.5}$		
FBQ0951+2635	2	1.246	0.260	AB	16.0 ± 2.0		
Q0957+561	2	1.413	0.36	AB	417.0 ± 1.5		
SDSS J1004+4112[b]	5	1.734	0.68	AB	40.6 ± 0.8	CA	821.6 ± 2.1
HE1104−1805	2	2.319	0.729	AB	$152.2^{+2.8}_{-3.0}$		
PG1115+080	4	1.735	0.310	A1B	11.7 ± 1.2	A2B	11.7 ± 1.2
				BC	25.0 ± 1.6	A1C	13.3 ± 1.0
				A2C	13.3 ± 1.0	A1A2	0.149 ± 0.006
RXJ1131−1231	4	0.658	0.295	AB	$12.0^{+1.5}_{-1.3}$	AC	$9.6^{+2.0}_{-1.6}$
				BC	2.2 ± 1.6	AD	87.0 ± 8.0
				BD	99.0 ± 8.0	CD	96.6 ± 8.0
B1422+231	4	3.620	0.337	AB	1.5 ± 1.4	AC	7.6 ± 2.5
				BC	8.2 ± 2.0		
SBS1520+530	2	1.855	0.717	AB	130.0 ± 3.0		
B1600+434	2	1.589	0.414	AB	51.0 ± 2.0		
B1608+656	4	1.394	0.630	AB	$31.5^{+2.0}_{-1.0}$	BC	36.0 ± 1.5
				BD	$77.0^{+2.0}_{-1.0}$	AC	4.5 ± 1.5
				AD	45.5 ± 1.5	CD	41.0 ± 1.5
SDSS J1650+4251	2	1.547	0.577	AB	49.5 ± 1.9		
PKS1830−211	2	2.507	0.89	AB	$26.0^{+4.0}_{-5.0}$		
HE2149−2745	2	2.033	0.603	AB	103.0 ± 12.0		

[a]See Oguri (2006) for references.

[b]See Fohlmeister et al. (2007).

for $H_\circ$ that depends only weakly on other cosmological parameters such as Ω_m and Ω_Λ (e.g., Schneider, Ehlers & Falco 1992). The determination of $H_\circ$ by measuring time delays does require that the mass distribution of the lens be determined accurately.

Small perturbations to the gravitational potential from other galaxies near the lens must also be taken into account. Observational efforts have often focused on measuring time delays, but have neglected the systematics of the mass distributions. Thus, measurements of $H_\circ$ inferred from different lens systems have been inconsistent. In recent years, additional "clean" lens systems (where the mass distribution of the lens is well constrained) have been analyzed in detail and the corresponding estimates of $H_\circ$ seem to be converging (see, e.g., Poindexter et al. 2007; Kochanek et al. 2006).

Currently, there are 17 GLS with 41 measured time delays (see Table 1). The relative uncertainties in the delays range between ~ 1 and 37%. The range reflects the difficulties of these measurements.

Oguri (2006) derived a statistical procedure based on two simple measures for each lens galaxy and lensed image pair: the degree of asymmetry and opening angle of each pair, relative to the center of each lens. He showed that based on the extant sam-

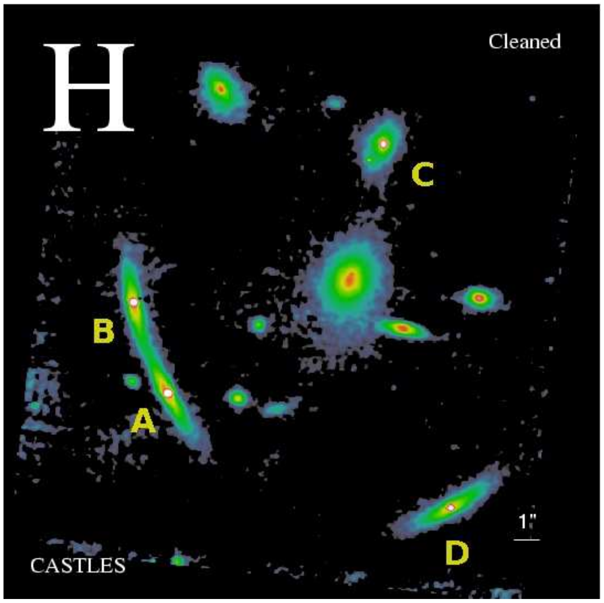

Fig. 6. SDSS J1004+4112, HST NICMOS H-band.

ple of time delays, the results are encouraging. The time delay results for $H_\circ$ agree with the HST Kep project estimate within about 10% errors. The results are limited by the small size of the sample of time delays, and by the assumed Gaussian distribution of measured time delays. Both of these will improve with larger samples that will also warrant studying different statistical distributions.

To become useful for cosmology, GLS must be observed with HST or similar, to obtain the best possible astrometry; monitoring is then required from the ground. Once we have a robust measurement of $H_\circ$, we can also turn around the idea and use time delays to constrain the mass distributions of GLS. Therefore, it is also worthwhile to monitor GLS even if they are not simple.

For the past 4 years, we have monitored several GLS in an attempt to estimate time delays and identify microlensing when it occurs (with J. Fohlmeister, J. Wambsganss and C. Kochanek). Among our targets is a wide-separation system, SDSS J1004+4112 (Inada et al. 2003). The system is set apart from "classic" quadruples because of its 15$''$ image separation and because it actually contains a 5th faint image (Inada et al. 2005). We observed SDSS J1004+4112 with HST NICMOS and ACS in 2004 (Figure 6). We obtained Sloan r-band lightcurves for the 4 brightest images between December 2003 and June 2007. We were able to determine the time delays for images A, B and C; Figure 7 shows the lightcurves. We found that A leads B by

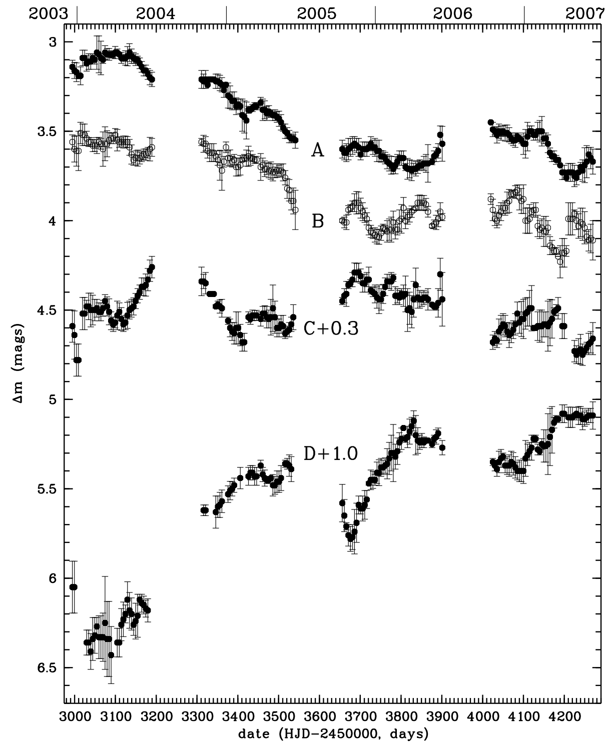

Fig. 7. Light curves for images A-D in SDSS J1004+4112 in the Sloan r band (Fohlmeister et al. 2007).

$\Delta t_{\rm BA} = 40.6 \pm 1.8$ days, and that image C leads image A by $\Delta\tau_{\rm CA} = 821.6 \pm 2.1$ days. For the last independent delay, we find a lower limit such that image D lags image A by $\Delta\tau_{\rm AD} > 1250$ days.

The presence of microlensing in SDSS J1004+4112 was first pointed out in spectra of the images (Richards et al. 2004). In addition to the intrinsic variations of the source quasar in SDSS J1004+4112 that we saw in images A-D (Figure 7), we confirmed that the images undergo microlensing (Figure 8) at the ~ 0.15 mag level in the r band. Based on our microlensing estimates for images A and B, we estimate an accretion disk size at a rest wavelength of 2300 Å of $10^{14.8\pm0.3}$ cm.

4. CONCLUSIONS

Our lightcurve measurements for the images A-D of SDSS J1004+4112 yield an estimate of the accretion-disk size of the lensed quasar. Unfortunately, the complexity of the lens, a cluster of galaxies, precludes a useful estimate of $H_\circ$. In spite of that, based on the delays and by assuming a value for $H_\circ$, we will be able to refine mass models for the lens cluster. The long delays allowed us to fill in the seasonal gaps and assemble a continuous, densely

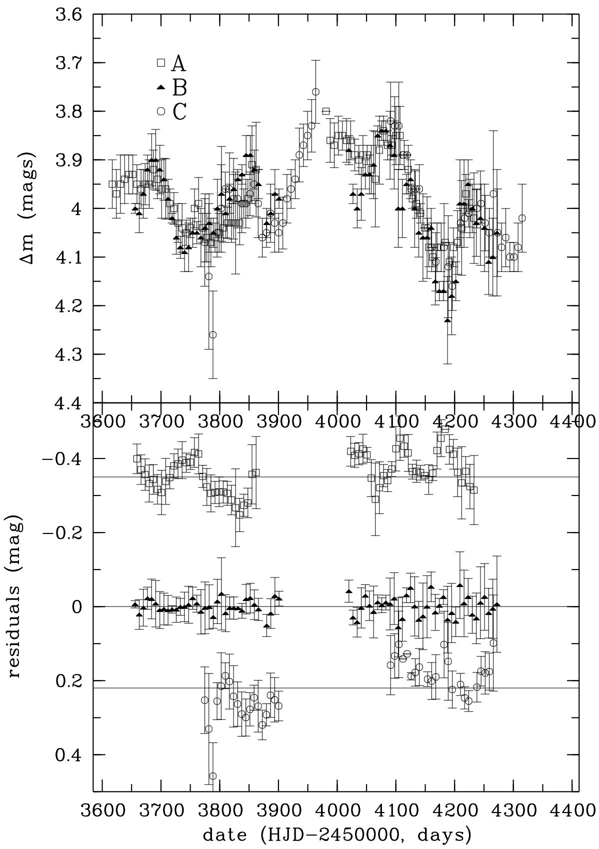

Fig. 8. Light curves for A-C in SDSS J1004+4112 (Fohlmeister et al. 2007), phased by the measured delays (upper panel). Residual magnitudes after subtraction of intrinsic variation (lower panel).

sampled light curve spanning 5.7 years whose variability implies a structure function with a logarithmic slope of $\gamma = 0.35 \pm 0.02$. As C is the leading image, sharp features in the C light curve can be intensively studied 2.3 years later in the A/B pair, potentially allowing detailed reverberation mapping studies of a quasar at minimal cost.

The current, growing sample of $\approx$ 100 strong lenses must grow significantly, at least to a few hundred GLS. When that level is reached, selection biases (e.g., radio, optical, serendipitous discovery) will be well understood and come under our control. The proposed Large Synoptic Survey Telescope (LSST) and the Panoramic Survey Telescope and Rapid Response System (PanSTARRS) surveys will take a complementary approach. These projects will periodically survey about 1/2 of the sky, and potentially will find thousands of new strong lenses.

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