PHYSICAL REVIEW D **84,** 123529 (2011)

Lensing time delays and cosmological complementarity

Eric V. Linder
Berkeley Lab and University of California, Berkeley, California 94720, USA
and Institute for the Early Universe WCU, Ewha Womans University, Seoul, Korea
(Received 19 September 2011; published 30 December 2011)

Time delays in strong gravitational lensing systems possess significant complementarity with distance measurements to determine the dark energy equation of state, as well as the matter density and Hubble constant. Time delays are most useful when observations permit detailed lens modeling and variability studies, requiring high resolution imaging, long time monitoring, and rapid cadence. We quantify the constraints possible between a sample of 150 such time delay lenses and a near term supernova program, such as might become available from an Antarctic telescope such as the KDUST and the Dark Energy Survey. Adding time delay data to supernovae plus cosmic microwave background information can improve the dark energy figure of merit by almost a factor 5 and determine the matter density Ω_m to 0.004, the Hubble constant h to 0.7%, and the dark energy equation of state time variation w_a to 0.26, systematics permitting.

DOI: 10.1103/PhysRevD.84.123529 PACS numbers: 98.80.−k, 95.36.+x

I. INTRODUCTION

Complementarity between cosmological probes increases their leverage on the cosmological model parameters, crosschecks results through differing systematic uncertainties, and breaks degeneracies. These all play important roles in elucidating the nature of our Universe: the energy densities in matter and dark energy, the scale of the Universe through the Hubble constant, and the characteristics of the dark energy behind the current cosmic acceleration.

Most probes, however, have substantial similarity in their parameter dependencies, involving the same combinations of ingredients entering into the Hubble parameter as a function of redshift, $H(z)$. Distances (and volumes), in particular, are essentially equivalent, and growth of structure also depends similarly on $H(z)$. Looking for a high degree of complementarity, especially to determine the dark energy equation of state value and time variation, [1] investigated the use of distance ratios present in strong gravitational lensing as a means of breaking this degeneracy.

While lensing distance ratios involve the mass structure of the lens, and so are not purely geometric, there has been impressive progress in modeling the mass distributions in lensing systems (e.g. [2–4]) and so it is worth considering strong lensing distances in more detail as a cosmological probe, in particular, for its complementarity. Here we revisit [1] with several important distinctions: (1) we concentrate on time delays, due to the recent observational successes [4,5] and modeling advances; (2) we consider a more realistic range of future observational prospects, involving projects starting to get underway, which will have important implications for complementarity; and (3) we carry out studies of the science reach as a function of redshift range, and in the presence of spatial curvature.

Several authors (e.g. [6–12]) have addressed the statistical power of strong lensing time delays from further future surveys such as LSST, calculating the numbers of lenses found and with measured time delays, and projecting possible Hubble constant or cosmological constraints. These, however, treat the lensing systems as an ensemble to average over, and in fact identify the mass modeling as a major uncertainty capable of degrading constraints substantially. Here we concentrate on what are sometimes called "golden lenses," although now the meaning is not systems with some special symmetry but rather ones where the survey design has specifically provided data enabling detailed construction of the lens mass model. The number of such systems will be much less, but we find they can have significant scientific leverage.

In Sec. II we discuss the cosmological impact of time delay measurements and their complementarity with other probes. Section III considers reasonable possibilities for survey data sets in terms of number and redshift range of time delay systems, and analyzes their constraints in conjunction with a midterm supernova (SN) survey and cosmic microwave background data. Survey requirement issues with respect to imaging resolution, time sampling, etc. for time delay measurement, lens modeling, and systematic error control are outlined in Sec. IV, with specific reference to the Antarctic optical/infrared telescope program.

II. TIME DELAYS AS A COSMIC PROBE

Strong gravitational lensing causes multiple images of distant sources, with the light rays from the images taking different amounts of time to propagate to the observer. The time delay involves two parts: a geometric delay from different path lengths and a gravitational time delay from traversing different values of the gravitational potential of the lens. Thus both the image positions and the lens mass model must be accounted for. Time delays are observed by looking for coordinated variations in the flux from the images, e.g. of time varying quasars, which requires long-time, well-sampled monitoring. Typical galaxy lens induced delays are ~60 days, and the desired measurement accuracy is a couple of days or better.

To translate the image angular positions into spatial positions, for computing both the path length and the gravitational potential effects, one needs the (conformal) distance to the lens, r_l, to the source, r_s, and between the source and lens, r_{ls}. Only in flat space is $r_{ls} = r_s - r_l$. The particular combination of distances central to time delays is

$$T \equiv \frac{r_l r_s}{r_{ls}}. \tag{1}$$

Specifically, following [5], the time delay of an image at position $\vec{\theta}$ on the sky relative to an unlensed source at position $\vec{\beta}$ is

$$\Delta t(\vec{\theta}, \vec{\beta}) = \frac{r_l r_s}{r_{ls}}(1 + z_l)\phi(\vec{\theta}, \vec{\beta}), \tag{2}$$

where the distance ratio is T, containing the key cosmological information, and ϕ is the Fermat or time delay potential given by

$$\phi(\vec{\theta}, \vec{\beta}) = \frac{(\vec{\theta} - \vec{\beta})^2}{2} - \psi(\vec{\theta}). \tag{3}$$

We see that the first term on the right-hand side is the geometric delay and the second term is the lensing potential delay with $\nabla^2\psi = 2\kappa$ for κ the dimensionless lensing projected surface mass density.

The time delay potential ϕ connecting T to the observed time delays therefore depends on the lens mass distribution, the model for which is built up from information on image positions and flux ratios and perhaps surface brightness morphologies, ideally from many images including arcs. See [4,5,10] for details on the modeling process and calculation of the potential factor. All the cosmological information comes from T (cf. the approach of [13]), with the uncertainties in the potential factor entering into the error propagation, together with measurement uncertainties.

The time delay probe T has interesting properties with regards to the cosmological parameter leverages. As noted by [1], the sensitivities to dark energy parameters w_0 and w_a, where the dark energy equation of state is well fit by $w(z) = w_0 + w_a z/(1 + z)$ [14], are actually positively correlated in contrast to standard distance measurements such as from type Ia supernovae. This offers hope for complementarity with such probes. Furthermore, the sensitivity to the dimensionless matter density Ω_m at low redshift is remarkably low compared to solo distances, leading to the possibility of breaking the usual degeneracy between the matter density and dark energy equation of state. Finally, the ratio depends linearly on the Hubble scale H_0^{-1}, and since [15] researchers have sought to use lensing time delays to measure the Hubble constant.

In Fig. 1 we highlight these special properties. The derivatives $\partial \ln T/\partial p$ give the sensitivities for each parameter p and are exactly what enters into a Fisher matrix analysis for cosmological parameter estimation. Raw (unmarginalized) sensitivities can be read directly; e.g. $\partial \ln T/\partial p/0.01 = 10$ means that a 1% measurement of T delivers an uncertainty $\sigma(p) = 0.1$. This must be folded in with the covariances between parameters: sensitivity curves having the same (reflected) shape indicate highly anticorrelated (correlated) parameters. For the time delay probe, the curve shapes are not very similar—a good sign for breaking degeneracies—and we see the unusual positive correlation between w_0 and w_a over the whole range $z_l = 0$–0.6 (where, for simplicity, we have assumed $z_s = 2z_l$).

To take advantage of the odd correlation properties of T to give strong complementarity in probing cosmology, we include type Ia supernova distances as another probe, having very different degeneracies. The supernova distance-redshift relation has no sensitivity to the Hubble constant $h = H_0/(100\ \mathrm{km/s/Mpc})$ however, this being convolved with the unknown supernova absolute luminosity. To profit from the time delay dependence on h, therefore, we also use CMB information, which determines the physical

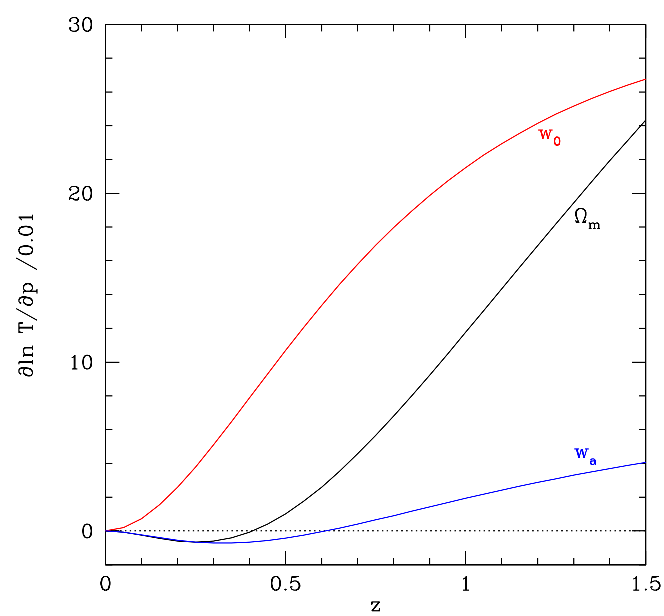

FIG. 1 (color online). Sensitivity of the time delay distance combination $T = r_l r_s/r_{ls}$ to the cosmological parameters is plotted vs lens redshift. Curves with opposite signs at the same redshift indicate positive correlations between those parameters—very unusual for the dark energy equation of state variables w_0 and w_a.

matter density combination $\Omega_m h^2$ very well (but not particularly Ω_m by itself). This further offsets the weak dependence of T alone on the matter density, and so the weakness of each is turned into strength in complementarity.

III. COSMOLOGICAL LEVERAGE

Another interesting property of the time delay probe is that its useful and unusual correlation properties occur at low redshift, for $z_l = 0$–0.6. Detailed observations of lensing systems will be easier there, where the lens galaxy and source images will not be as faint as at higher redshift. We therefore take as our baseline a survey producing time delay measurements at $z_l = 0.1$–0.6 (there is relatively little volume for lensing systems below $z_l = 0.1$), and then study variations of this. For simplicity, we fix $z_s = 2z_l$; although there will be a distribution of source redshifts, this has little impact on the cosmology estimation (see, e.g., Sec. 5.5 of [7]), and we have explicitly checked that using instead $z_s = 4z_l$ affects the dark energy figure of merit (uncertainty area) result by less than 1%. In most of this section we assume a spatially flat universe, studying the effect of an additional parameter for curvature in Sec. III B.

A. Cosmological parameter constraints

To the time delay measurements we add SN distance and CMB information and carry out a Fisher matrix analysis to estimate the cosmological parameter constraints. For the supernovae, we take a midterm sample reasonable for the next five years, consisting of 150 SN at $z = 0.03$–0.1 from the Nearby Supernova Factory [16], 100 SN per 0.1 bin in redshift from $z = 0.1$–1 as from the Dark Energy Survey (DES: [17]) with follow-up spectroscopy, and 42 SN between $z = 1$–1.7 as from Hubble Space Telescope observations such as the CLASH [18] and CANDELS [19] surveys. This seems like a reasonable estimate for a midterm, well-characterized supernova sample. Each supernova is given a 0.15 mag (7% in distance) statistical uncertainty, and each redshift bin of 0.1 has a systematic floor at $dm_{\rm sys} = 0.02(1 + z)$ added in quadrature to the statistical error. Thus the supernova sample is systematics limited out to $z = 1$. For CMB data, we take Planck quality information consisting of determination of the geometric shift parameter R to 0.2% and the physical matter density $\Omega_m h^2$ to 0.9%, roughly corresponding to constraints from the location and amplitude, respectively, of the temperature power spectrum acoustic peaks. The parameter set is $\{\Omega_m, w_0, w_a, h, \mathcal{M}\}$, where $\mathcal{M}$ is the convolution of the supernova absolute luminosity and the Hubble constant.

Current measurements can deliver the time delay probe T to $\sim$5% for a lensing system, dominated by systematic uncertainties for individual systems. With a survey designed to find many strong lensing images and characterize them accurately, it may be possible to consider 1% measurements of T in each redshift bin of 0.1 from $z = 0.1$–0.6. This can be thought of as either 25 strong lenses per bin (150 total), or fewer lenses with better accuracy than 5% per system from a survey designed to gather data needed to control systematics, or a combination of the two. We discuss the survey requirements in Sec. IV.

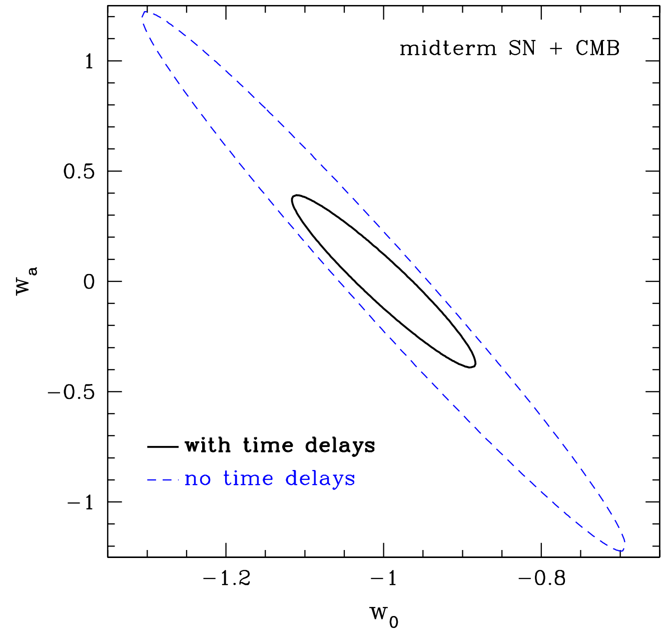

FIG. 2 (color online). We show 68% confidence level constraints on the dark energy equation of state parameters w_0 and w_a using midterm supernova distances and CMB information, and with (solid curve) or without (dashed curve) time delay measurements. The time delay probe demonstrates strong complementarity, tightening the area of uncertainty by a factor 4.8.

Figure 2 shows the dramatic improvement in the dark energy equation of state parameters (marginalized over the other parameters) when adding the time delay probes of 1% accuracy over $z = 0.1$–0.6. The area of the error contour in w_0–w_a tightens by a factor 4.8 over that from SN + CMB alone. All the cosmological parameters are better determined by factors of 2.6–3.1. Time delays therefore have great complementarity with the supernova and CMB probes, and such a strong lensing survey would be highly valuable scientifically.

The absolute level of the constraints with time delays is impressive as well. The Hubble constant is determined to 0.0051, or 0.7%, the matter density Ω_m to 0.0044 (1.6%), and the present value of the dark energy equation of state w_0 to 0.077 and its time variation w_a to 0.26. While falling short of the results from a space survey of supernovae (with CMB), such a midterm program could deliver important insights into the nature of cosmic acceleration and the cosmological model.

The baseline time delay sample adopted seems plausible, but let us consider variations to see how the cosmological constraints depend on the survey characteristics. It may be difficult to find enough strong lens systems at the lowest redshifts, due to the limited volume. Note, however, that the SLACS survey has been successful in detecting lenses [20], if not necessarily measuring time delays, at $z_l \approx 0.1$, and this depends on the source population targeted. Nevertheless, if we cut the time delay information to the range $z = 0.3$–0.6 (so 100 strong lenses), we find that this reduces the figure of merit (inverse uncertainty area) by 25%. The greatest effect is on the Hubble constant determination, since this is what low redshift time delays excel at, with $\sigma(h)$ degrading by 55%. This then propagates into the Ω_m constraint, which weakens by 41%. These can be somewhat ameliorated if we have some information from $z = 0.1$–0.2; e.g. using 12 rather than 50 time delays in this range recovers almost half the constraining power.

Conversely, suppose that a strong lensing time delay survey could be extended out to $z_l = 1$, still at the 1% accuracy per 0.1 redshift bin. Then the figure of merit improves by 40%, though the constraints on Ω_m and h only gain by 6%. Detailed characterization of the lensing systems at such high redshift could be problematic, however, due to lower fluxes and signal to noise. The redshifts of well-characterized time delay systems is slowly being pushed out toward $z_l = 1$ [21,22].

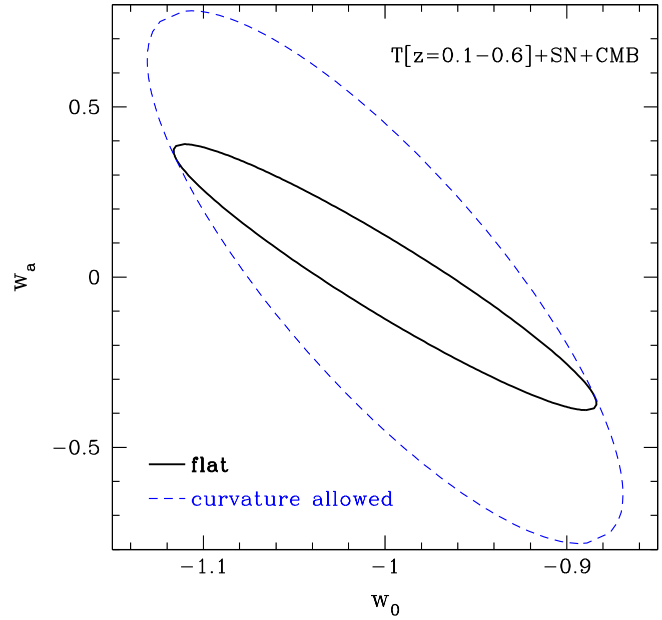

FIG. 3 (color online). We show 68% confidence level constraints on the dark energy equation of state parameters w_0 and w_a using time delay, midterm supernovae, and CMB information, assuming spatial flatness (solid curve) or allowing curvature (dashed curve). The time delay probe moderates the curvature degeneracy, restricting the area degradation to a factor 4, rather than 20 without time delay data.

B. Including curvature

Spatial curvature enters together with the Hubble parameter into either the angular or luminosity distance between observer and source. Degeneracy between the curvature density $\Omega_k = 1 - \Omega_m - \Omega_{de}$ and dark energy equation of state can be severe; for example, see Fig. 6 of [23] for effects on w_0, w_a or [24] for general $w(z)$. This can be broken by using a wide redshift range of distances; in particular, high and low redshift distance measurements can separate the curvature density from other components. Another possibility is direct measurement of the Hubble parameter as well as distances (e.g. from the radial baryon acoustic oscillation scale), or distance ratios appearing in gravitational lenses or large scale structure (see, e.g., [25–27]). This has the advantage of not necessarily requiring high redshift measurements.

We now examine the role that time delay measurements can play in breaking the curvature degeneracy, if the Universe is not assumed to be spatially flat. Figure 3 shows the results when we allow for curvature in the cosmology fitting, using time delays, supernovae distances, and CMB information.

The dark energy equation of state uncertainty indeed degrades, with the area figure of merit declining by a factor 4.1. This shows the degeneracy is not fully broken, but should be contrasted with the factor 20.2 degradation from including curvature with only the SN + CMB data for a constraint. Thus the time delay probe is a useful tool even/especially when allowing for spatial curvature. Most of the covariance affects the time variation w_a, with its uncertainty doubling. The present value w_0 is only determined 12% worse, and the errors on Ω_m and h increase by 29% and 27%. The curvature itself is estimated to $\sigma(\Omega_k) = 0.0063$.

IV. SURVEY CHARACTERISTICS

In order to use time delays as a cosmological probe in the individual lensing system approach, the survey must deliver detections and accurate measurements of the time delays, detailed modeling of the lens systems, and control of other systematic uncertainties. Systematics include microlensing that induces variability, differentially altering the images' light curves, and projected mass not truly part of the lens, altering the mass modeling.

To detect a large sample of time delay systems, a wide field survey is needed, but to characterize them through accurate image positions, splittings, and flux variations requires high resolution imaging. Interestingly, a telescope at an excellent seeing site such as Dome A, Antarctica [28] could fulfill both roles. The Kunlun Dark Universe Telescope (KDUST: [29]), a 2.5 m telescope planned for Dome A, would be situated above the low ground layer and possibly have 0.3″ median seeing in the optical, 0.2″ in the low background noise infrared.

The advantages of high resolution imaging for strong lensing are crucial and manifold [9,30]. Such seeing also helps to separate the images from contamination by the lens galaxy light. To take advantage of this excellent seeing for strong lensing, the point spread function (PSF) would need to be stable, or algorithms developed to fit simultaneously the PSF and lens mass model. The stable winter weather, with low winds and large isoplanatic angle, at Dome A could be advantageous. KDUST surveys would overlap with Dark Energy Survey fields, as well as those of the South Pole Telescope and LSST. DES could supply much of the supernova sample, although supernova programs, at either low or very high redshift, are also being studied for KDUST [31].

Measuring time delays accurately from detected strong lensing systems requires a long time baseline, since the time delay distribution of interest is in the range of ~10–100 days. The long Antarctic night offers advantages here of continuity, although end effects from the long Antarctic day mean that not all systems at the upper end of this distribution will be usable, in particular, the longer cluster lenses (which also likely have larger external mass effects). Dense time sampling enables accurate time delay determination and ameliorates the effect of microlensing systematics, and again the Antarctic site allows continuous viewing of fields and regular sampling, every 24 hours or even more often. (Indeed, detection of time delay perturbations can be used as a probe of dark matter substructure and properties [32].) While photometric redshifts are likely good enough to remove most projected mass contamination, follow-up spectroscopy for accurate determination of the redshifts of the images and lens constituents is necessary. A spectrographic telescope is being considered for Dome A, but spectroscopy is needed in any case for DES fields (e.g. for the supernovae), so KDUST gains a further advantage from synergy with DES.

The prospects for 1% measurement of the time delay-redshift relation in a 0.1 bin in redshift for lenses at $z = 0.1$–0.6 seem reasonable. Improvements in control of systematics could tighten the current 5% accuracy, and such surveys will build the statistics as well. The number of time delay systems baselined in this article—150, a 1 order of magnitude increase over current levels—is plausible, as is the range of supernovae data, making the science case for time delay surveys of interest for further investigation.

V. CONCLUSIONS

We have quantified the significant complementarity as cosmological probes that strong gravitational lensing time delays, involving distance ratios, have with solo distance measurements such as from type Ia supernovae. A well-designed time delay survey can add to practical, near-term supernova and CMB data to provide surprisingly incisive constraints on the dark energy equation of state, the Hubble constant, and the matter density. The improvement in equation of state area uncertainty (figure of merit) is almost a factor 5 over the data sets without time delays.

Time delays also significantly ameliorate the degeneracies in parameter determination caused by allowing for spatial curvature, again improving the area uncertainty by a factor 5. Determination of the Hubble constant to 0.7% as well would be valuable for several astrophysical and cosmological applications.

We have focused on what seem to be near-term, reasonable data sets. An exciting possibility for achieving these is telescopes being developed at promising Antarctic astronomical sites, such as KDUST at Dome A. If these truly deliver high resolution, stable seeing much better than conventional ground based optical conditions (if not quite space quality), the baseline time delay survey considered here to deliver 1 order of magnitude times larger sample of well-characterized time delay systems appears practical. Another advantage is the synergy with other southern surveys, such as the Dark Energy Survey in the near term. (While we have intentionally not extrapolated to long-term developments, synergy with LSST is clear as well.)

Systematic uncertainties would be ameliorated by the high resolution imaging, whether single epoch to characterize in detail the lens model and separate the host galaxy light, or multiepoch to finely measure the flux variations and measure clean and accurate time delays. The redshift range for the survey could be modest, $z_l \approx 0.1$–0.6, and we presented how the cosmological constraints change if a narrower or wider range is considered.

In attempting to stay within straightforward practicality, we have not discussed exciting ideas such as testing for deviations from general relativity. After all, the same principle is used in the solar system, with spacecraft signal time delays providing stringent limits on other gravity theories; also, some screening mechanisms that restore gravity to general relativity are expected to kick in on scales accessible to cosmological strong lensing [33–35]. Many other astrophysical applications exist for a high resolution imaging survey (especially with low noise in the infrared), such as using strong lenses as gravitational telescopes to study early structures and the epoch of reionization.

Complementarity between cosmological probes offers the strongest and most robust leverage for revealing the scale and contents of our Universe, and the nature of the cosmic acceleration. The combination of time delays, supernova distances, and CMB data provides an exciting level of insight with near-term surveys.

ACKNOWLEDGMENTS

I gratefully acknowledge Sherry Suyu for helpful discussions, and thank the Niels Bohr International Academy and Dark Cosmology Centre, University of Copenhagen for hospitality during the workshop inspiring this research. This work has been supported in part by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 and by World Class University Grant No. R32-2009-000-10130-0 through the National Research Foundation, Ministry of Education, Science and Technology of Korea.

[1] E. V. Linder, Phys. Rev. D **70**, 043534 (2004).
[2] S. H. Suyu, P. J. Marshall, R. D. Blandford, C. D. Fassnacht, L. V. E. Koopmans, J. P. McKean, and T. Treu, Astrophys. J. **691**, 277 (2009).
[3] F. Courbin *et al.*, Astron. Astrophys. **536**, A53 (2011).
[4] R. Fadely, C. R. Keeton, R. Nakajima, and G. M. Bernstein, Astrophys. J. **711**, 246 (2010).
[5] S. H. Suyu, P. J. Marshall, M. W. Auger, S. Hilbert, R. D. Blandford, L. V. E. Koopmans, C. D. Fassnacht, and T. Treu, Astrophys. J. **711**, 201 (2010).
[6] M. Oguri and P. J. Marshall, Mon. Not. R. Astron. Soc. **405**, 2579 (2010).
[7] D. Coe and L. Moustakas, Astrophys. J. **706**, 45 (2009).
[8] B. M. Dobke, L. J. King, C. D. Fassnacht, and M. W. Auger, Mon. Not. R. Astron. Soc. **397**, 311 (2009).
[9] L. V. E. Koopmans *et al.*, arXiv:0902.3186.
[10] M. Oguri, Astrophys. J. **660**, 1 (2007).
[11] G. F. Lewis and R. A. Ibata, Mon. Not. R. Astron. Soc. **337**, 26 (2002).
[12] K. Yamamoto, Y. Kadoya, T. Murata, and T. Futamase, Prog. Theor. Phys. **106**, 917 (2001).
[13] D. Paraficz and J. Hjorth, Astron. Astrophys. **507**, L49 (2009).
[14] E. V. Linder, Phys. Rev. Lett. **90**, 091301 (2003).
[15] S. Refsdal, Mon. Not. R. Astron. Soc. **128**, 307 (1964).
[16] http://snfactory.lbl.gov; G. Aldering *et al.*, Proc. SPIE Int. Soc. Opt. Eng. **4836**, 61 (2002).
[17] http://www.darkenergysurvey.org.
[18] M. Postman *et al.*, arXiv:1106.3328.
[19] N. A. Grogin *et al.*, Astrophys. J. Suppl. Ser. **197**, 35 (2011).
[20] A. S. Bolton, S. Burles, L. V. E. Koopmans, T. Treu, R. Gavazzi, L. A. Moustakas, R. Wayth, and D. J. Schlegel, Astrophys. J. **682**, 964 (2008).
[21] S. Suyu (private communication).
[22] F. Courbin (private communication); M. Tewes (to be published).
[23] E. V. Linder, Astropart. Phys. **24**, 391 (2005).
[24] A. Shafieloo and E. V. Linder, Phys. Rev. D **84**, 063519 (2011).
[25] L. Knox, Phys. Rev. D **73**, 023503 (2006).
[26] G. Bernstein, Astrophys. J. **637**, 598 (2006).
[27] E. V. Linder, Phys. Rev. D **68**, 083503 (2003).
[28] W. Saunders *et al.*, Publ. Astron. Soc. Pac. **121**, 976 (2009); J. S. Lawrence *et al.*, Publ. Astron. Soc. Pac. **26**, 379 (2009).
[29] http://www.kdust.org.
[30] J. Richard, J-P. Kneib, M. Limousin, A. Edge, and E. Jullo, Mon. Not. R. Astron. Soc. **402**, L44 (2010).
[31] A. Kim *et al.*, Astropart. Phys. **33**, 248 (2010).
[32] C. R. Keeton and L. A. Moustakas, Astrophys. J. **699**, 1720 (2009).
[33] T. L. Smith, arXiv:0907.4829.
[34] F. Schmidt, Phys. Rev. D **81**, 103002 (2010).
[35] B. Jain and J. Khoury, Ann. Phys. (N.Y.) **325**, 1479 (2010).