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Precise Measurements of the Speed of Light with High-redshift Quasars: Ultra-compact Radio Structure and Strong Gravitational Lensing

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Abstract

Although the speed of light has been measured with very high precision, most of these measurements were carried out on Earth or in our close cosmic surroundings. In this Letter, we propose an original idea to combine the observations of ultra-compact structure in radio quasars and strong gravitational lensing with quasars acting as background sources to estimate the speed of light. The method will provide precise measurements of the speed of light using extragalactic objects at different redshifts. We evaluate if current or future missions such as the Large Synoptic Survey Telescope (LSST) and Dark Energy Survey (DES) can be sensitive enough to detect any variation of c. Our results show that strongly lensed quasars observed by LSST would produce robust constraints on $\Delta c/c$ at the level of 10^{-4}, if the compact radio structure measurements are available.

Unified Astronomy Thesaurus concepts: Quasars (1319); Strong gravitational lensing (1643); Cosmological parameters (339); Radio sources (1358)

1. Introduction

As one of the most fundamental and recognized physical properties in modern astrophysics, the constancy of the speed of light c in free space plays a very important role in basic physical laws including Maxwell equations and Einstein's relativity. However, the theories of dynamical speed of light have already been considered by Einstein himself (Einstein 1907). More recent interest in varying the speed of light was triggered by the conjecture that they could become an alternative to the inflationary mechanism of solving standard cosmological problems (Albrecht & Magueijo 1999; Barrow 1999; Barrow & Magueijo 1999). Davies et al. (2002) claimed that variation of the speed of light can be discriminated from variation of the elementary charge based on the entropy of black holes, which was later refuted by Carlip & Vaidya (2003) and Flambaum (2009). It has been argued by Duff (2002) that only the time variation of dimensionless constants of nature is a legitimate subject of enquiry, and that dimensional constants such as c, $\bar{h}$, and G are merely human constructs whose value has no operational meaning. This was subsequently refuted by Moffat (2002), who pointed out that such varying dimensional constants can have significant physical consequences for the universe that can be directly measured in experiments and that postulating that dimensional constants vary in time can significantly change the laws of physics. It is worth recalling that Ellis & Uzan (2005) gave a sobering review o the serious conceptual problems one faces while trying to change the status of c in physics. In particular, they stressed that it is usually not consistent to allow a constant to vary in an equation that has been derived from a variational principle under the hypothesis of this quantity being constant. Therefore, one needs to go back to the Lagrangian and derive new equations after having replaced the constant by a dynamical field. On the tide of the growing popularity of the varying speed of light (VSL) approach, this idea has also attracted a lot of interest recently within the framework of the so-called rainbow gravity theories, in which Lorentz invariance is broken (c basically depending on energy rather than time) based on the modified dispersion relations that include Planck energy as a second invariant (Mattingly 2005; Pan et al. 2015, 2019).

Although c has been measured with very high precision, however, most of these measurements were carried out on Earth or in our close cosmic surroundings (c_0). Precise measurements of the speed of light using extragalactic objects seem to be still missing. In fact, some recent works focused on simulated baryon acoustic oscillations data to detect the variation of the speed of light (Salzano et al. 2015), which can be measured through the quantity $D_A(z_m)H(z_m)/c_0$, where $D_A(z)$ is the angular diameter distance, $H(z)$ is the Hubble parameter, and c_0 is the speed of light measured here and now. More recently, Cao et al. (2017a) showed that real observations of the compact structure in radio quasars, combined with measurements of Hubble parameters, can be used to obtain the speed of light at z_m (the maximum redshift is covered by such observational data set) and probe the constancy of the speed of light referring to the redshift baseline $z = 1.70$. The result was in perfect agreement with the value c_0 measured "here and now" (i.e., at $z = 0$), which, according to standard physics should be a universal constant of nature. However, the drawback of this method is that only one measurement of c can be obtained, referring to the redshift where $D_A(z)$ reaches its maximum ($z = 1.70$). Some other observational tests for VSL cosmologies have also been suggested (Cai et al. 2016; Cao et al. 2018), with independent observations of luminosity distances from type Ia supernovae (SNe Ia) acting as standard candles (Suzuki et al. 2012).

The power of modern cosmology lies in building up consistency rather than in single, precise, crucial experiments, which implies that every alternative method of measuring the speed of light is desired. In particular, the measurements of c in the distant universe is an almost completely uncharted territory. Therefore, a new cosmological window would open if we could extend the c measurements using new, deeper astronomical probes in a redshift range well beyond the limit of Ia SNe. More promising candidates in this context are quasars, the brightest sources in the universe, which can be observed up to very high redshifts and have always been considered as potential candidates to extend the distance ladder (Cao et al. 2017b). Meanwhile, illuminated by the well-known gravitational lens Q0957+561 (Walsh et al. 1979), with the appearance of two images of $z_s = 1.41$ quasar within an Einstein radius of 3.″08 around the core of the lensing galaxy at $z_l = 0.36$, galactic-scale strong lensing provides a very important astrophysical tool allowing us to use individual lensing galaxies to derive the source/lens distance ratio (Biesiada et al. 2010; Cao et al. 2012b, 2012a, 2015). In this Letter, we will focus on the idea of constraining c using observations of quasars: ultra-compact structure in radio quasars (Cao et al. 2017a, 2017b) and the effect of strong gravitational lensing with quasars acting as background sources (Young et al. 1981). This opens up the possibility of measuring the speed of light on the baseline up to the redshift of the source quasar.

2. Methodology

Following Einstein's theory of general relativity, one concludes that light will be deflected by masses, irrespective of their physical state or composition. In the case when the background source, the intervening lens, and the observer are perfectly aligned, the source is imaged as the so-called Einstein ring. Its radius sets the angular scale of separation between multiple images in realistic (slightly misaligned) systems.

In this work we focus on strong-lensing systems where the early-type galaxies dominate the population of lenses, with a higher-redshift quasar acting as the source (Walsh et al. 1979). Following a recent analysis (Rusin & Kochanek 2005; Koopmans et al. 2006, 2009; Cao et al. 2016), the mass distribution of massive elliptical galaxies within the effective radius can be reasonably characterized by an isothermal ellipsoid. However, one can still expect the deviation from the isothermal profile and the rigid assumption of the singular isothermal sphere (SIS) model for the lens. In this paper, we will consider a more general, spherically symmetric power-law mass distribution ($\rho \sim r^{-\gamma}$), which has been widely used in studies of lensing caused by early-type galaxies (Treu et al. 2006; Cao et al. 2012b, 2015; Ma et al. 2019).

After solving the spherical Jeans equation (Koopmans 2006) based on the assumption that stellar and mass distributions follow the same power law and velocity anisotropy vanishes, the combination of the mass inside the Einstein radius and the dynamical mass inside the aperture $\theta_{\rm ap}$ projected to the lens plane leads to the following expression (Cao et al. 2015) for the Einstein radius:

$$\theta_E = 4\pi \frac{\sigma_{\rm ap}^2}{c_{z_s}^2} \frac{D_{A,ls}}{D_{A,s}} \left(\frac{\theta_E}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma) \tag{1}$$

where

$$f(\gamma) = -\frac{1}{\sqrt{\pi}} \frac{(5-2\gamma)(1-\gamma)}{3-\gamma} \frac{\Gamma(\gamma-1)}{\Gamma(\gamma-3/2)} \times \left[\frac{\Gamma(\gamma/2-1/2)}{\Gamma(\gamma/2)}\right]^2 \tag{2}$$

and $\sigma_{\rm ap}$ represents the luminosity-averaged line-of-sight velocity dispersion of the lens inside the aperture $\theta_{\rm ap}$, c_{z_s} is the speed of light related to the baseline from the source (at redshift $z = z_s$) to the observer (at redshift $z = 0$), $D_{A,ls}$ and $D_{A,s}$ are the angular diameter distances between the lens and source and between the observer and source. Assuming the Friedman–Robertson–Walker metric, one can relate the angular diameter distance D_A and the proper distance D according to $D_A(z_1, z_2) = D(z_1, z_2)/(1 + z_2)$. In the general FRW metric, comoving distances are additive according to the so-called distance sum rule $D_{ls} = \sqrt{1 + \Omega_k D_l^2}\, D_s - \sqrt{1 + \Omega_k D_s^2}\, D_l$ (Räsänen et al. 2015; Cao et al. 2019; Qi et al. 2019a, 2019b). Therefore, the distance ratio $D_{A,ls}/D_{A,s}$, derivable from lensing systems, can be expressed in terms of angular diameter distances between lens and observer ($D_{A,l}$) and between source and observer ($D_{A,s}$)

$$\frac{D_{A,ls}}{D_{A,s}} = \sqrt{1 + \Omega_k (1+z_l)^2 D_{A,l}^2} - \frac{1+z_l}{1+z_s} \frac{D_{A,l}}{D_{A,s}} \sqrt{1 + \Omega_k (1+z_s)^2 D_{A,s}^2}. \tag{3}$$

We will, however, limit ourselves to the flat FRW model, which is considerably supported by observational data. In this case Equation (3) reduces to

$$\frac{D_{ls}}{D_s} = 1 - \frac{1+z_l}{1+z_s} \frac{D_l}{D_s}. \tag{4}$$

By combining Equations (1)–(4), one can express the speed of light as

$$c_{z_s} = \sigma_{\rm ap} \sqrt{\frac{4\pi}{\theta_E} \left(1 - \frac{1+z_l}{1+z_s} \frac{D_l}{D_s}\right) \left(\frac{\theta_E}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma)} \tag{5}$$

which is suggestive of how to measure this quantity using strong-lensing systems.

From the observational point of view, the Einstein radius θ_E can be determined from image astrometry for individual lenses, γ can be estimated from high-resolution imaging (Vegetti et al. 2010; Wong et al. 2015), while the measurement of the stellar velocity dispersion $\sigma_{\rm ap}$ could be obtained from the lens spectroscopy. There remains the term involving the distance ratio $D_{A,l}/D_{A,s}$. One could be tempted to presume cosmological model, e.g., a flat ΛCDM with $\Omega_m = 1 - \Omega_\Lambda = 0.3$, and calculate this ratio knowing the redshifts, but this would introduce a bias concerning the model itself, as well as its parameters. A more reasonable approach is to derive the distances to the lens and to the source by just referring to their redshifts and the absolute distances of standard candles or standard rulers located at these redshifts. As for the standard candles, where SN Ia are prime candidates (for properly calibrated gamma-ray bursts we should still wait), but they cover the range of redshifts $z < 1.40$, which is too close compared to the distant quasars. Instead, we propose that the quasars themselves can be reliable sources of D_A. In other words, one may turn to the angular size of the compact structure in radio quasars from the very-long-baseline interferometry (VLBI) observations and use them as standard rulers at different redshifts. More specifically, a recently compiled milliarcsecond compact radio-sources data set comprising 120 intermediate-luminosity quasars covering the redshift range $0.46 < z < 2.76$, could be used. In this sample, the linear size of the standard ruler has been calibrated to $l_m = 11.03$ pc through a new cosmology-independent technique (Cao et al. 2017b).

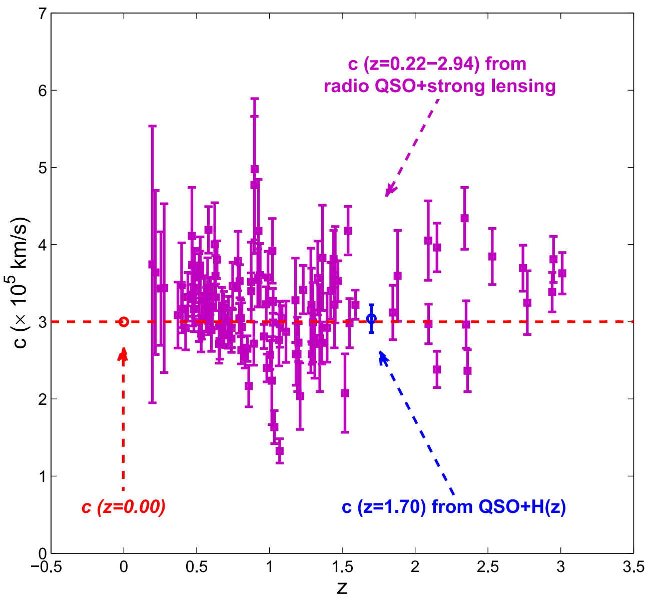

Figure 1. Individual measurements of the speed of light from current observations of radio quasars and strong-lensing systems.

Through the directly observable quantity in this data set, which is the angular size $\theta(z)$ of the compact structure in radio quasars, we could obtain the $D_A(z)$ both at lens and source redshifts as

$$D_A(z) = \frac{l_m}{\theta(z)}. \tag{6}$$

matching in redshift pairs of compact radio sources to the lens and the quasar, respectively.

Note, however, that since we need the distance ratio $D_{A,l}/D_{A,s}$ only, the inclusion of the angular size $\theta(z)$ into the measurements of c is also beneficial in alleviating the systematics caused by the determination of the linear size of this standard ruler l_m. Therefore, the expression for the speed of light can be rewritten as

$$c_{z_s} = \sigma_{\rm ap}\sqrt{\frac{4\pi}{\theta_E}\left(1 - \frac{1+z_l}{1+z_s}\frac{\theta(z_s)}{\theta(z_l)}\right)\left(\frac{\theta_E}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma)}. \tag{7}$$

It is obvious that combining $\sigma_{\rm ap}$, θ_E, $\theta_{\rm ap}$,and γ obtained from observations of galactic-scale strong-lensing systems with the quasars as sources, and the measurements of $\theta(z_s)$ and $\theta(z_l)$ derived from the observations of compact structure in radio quasars, will introduce considerable uncertainties into the measurement of c. We will first use the current observations of ultra-compact structure in radio quasars and strong gravitational lensing systems to test, model-independently, the speed of light at different redshifts. In our analysis, the observational angular size ratio, $\theta(z_s)/\theta(z_l)$, are determined by the data based on a 2.29 GHz VLBI all-sky survey of 120 milliarcsecond ultra-compact radio quasars (Cao et al. 2017a). However, large uncertainties of the angular size measurements make it impossible to determine $\theta(z_s)$ and $\theta(z_l)$ precisely. Therefore, we use a powerful reconstruction method (Seikel et al. 2012) based on Gaussian processes (GPs). Our quasar sample is sufficient to reconstruct the profile of $\theta(z)$ up to the redshifts $z \sim 3$. It is therefore reasonable to disregard the SGL systems with $z_s < 3.0$ in the analysis. Due to the limited size of available quasar-galaxy lensing systems, we used a sample of 118 strong-lensing systems where both quasars and galaxies acted as sources. This sample comes from the Sloan Lenses ACS (SLACS), Strong Lensing Legacy Survey (SL2S), BOSS emission line lens survey (BELLS), and Lens Structure and Dynamics (LSD) survey and the source redshift covers the range $0.22 < z_s < 2.94$. The relevant information necessary to perform statistical analysis, including the redshifts of both lens and source, Einstein radii, and aperture radius, as well as the stellar kinematic measurements, was summarized in Cao et al. (2015) and Shu et al. (2017). Concerning the radial mass distribution of early-type galaxies, we use the spherically symmetric isothermal mass distribution ($\gamma = 2.0$) as the lens model, which has been extensively used in recent studies of lensing caused by early-type galaxies (Koopmans et al. 2006, 2009; Treu et al. 2006; Cao et al. 2012a). The measurements of the speed of light from $z_s = 0.22$ to $z_s = 2.94$ are shown in Figure 1. Following the most straightforward and popular way of summarizing multiple measurements, i.e., inverse variance weighting, our final assessment of the speed of light is $c(z_s) = 3.005(\pm 0.060) \times 10^5$ km s^{-1}. Compared with the previous measurement of c (at $z = 1.70$) with the quasar sample and the expansion rate function $H(z)$ (Cao et al. 2017a), we can achieve more stringent constraints on the speed of light at different redshifts referring to the distant past (which is especially important in cosmology). Moreover, our results are also in perfect agreement with the value $c_0 \equiv 2.998 \times 10^5$ km s^{-1} measured "here and now."

Let us note that, at the current technique level, in spite of the high-resolution imaging concerning the lensing systems, uncertainties in the spectroscopic observations of stellar kinematics of the lens galaxy could cause ~10% statistical uncertainties of the c determination. Fortunately, in the near future we may pin our hope on improved depth, area, resolution, and sample sizes brought by the next generation of wide and deep sky surveys (Marshall et al. 2005), which will considerably improve the constraints on c. Now we will illustrate what kind of result one could get using the future data from the forthcoming surveys including the Dark Energy Survey (DES) and Large Synoptic Survey Telescope (LSST) survey.

3. Simulated Data and Constraints

The detailed calculation of the likely yields of several planned strong-lensing surveys was first realized by Oguri & Marshall (2010). Considering the realistic distributions for the lens and source properties, they found that upcoming wide-field synoptic surveys should detect several thousand lensed quasars. In particular, LSST should find more than some 8000 lensed quasars, while about 1000 lensed quasars will be detected by DES. Following the method proposed by Collett (2015), we first build a population of realistic strong lenses and then simulate observations of these lenses for DES and LSST. When calculating the sampling distribution (number density) of lensed quasars expected for the baseline survey planned with LSST, we adopt the differential rate of lensed quasar events as a function of z_s, based on the standard double power law for the quasar luminosity function (LF) calibrated by strong-lensing effects (Oguri & Marshall 2010). Because elliptical galaxies dominate in the quasar-galaxy lensing cross section, in our analysis we considered only quasars lensed by early-type

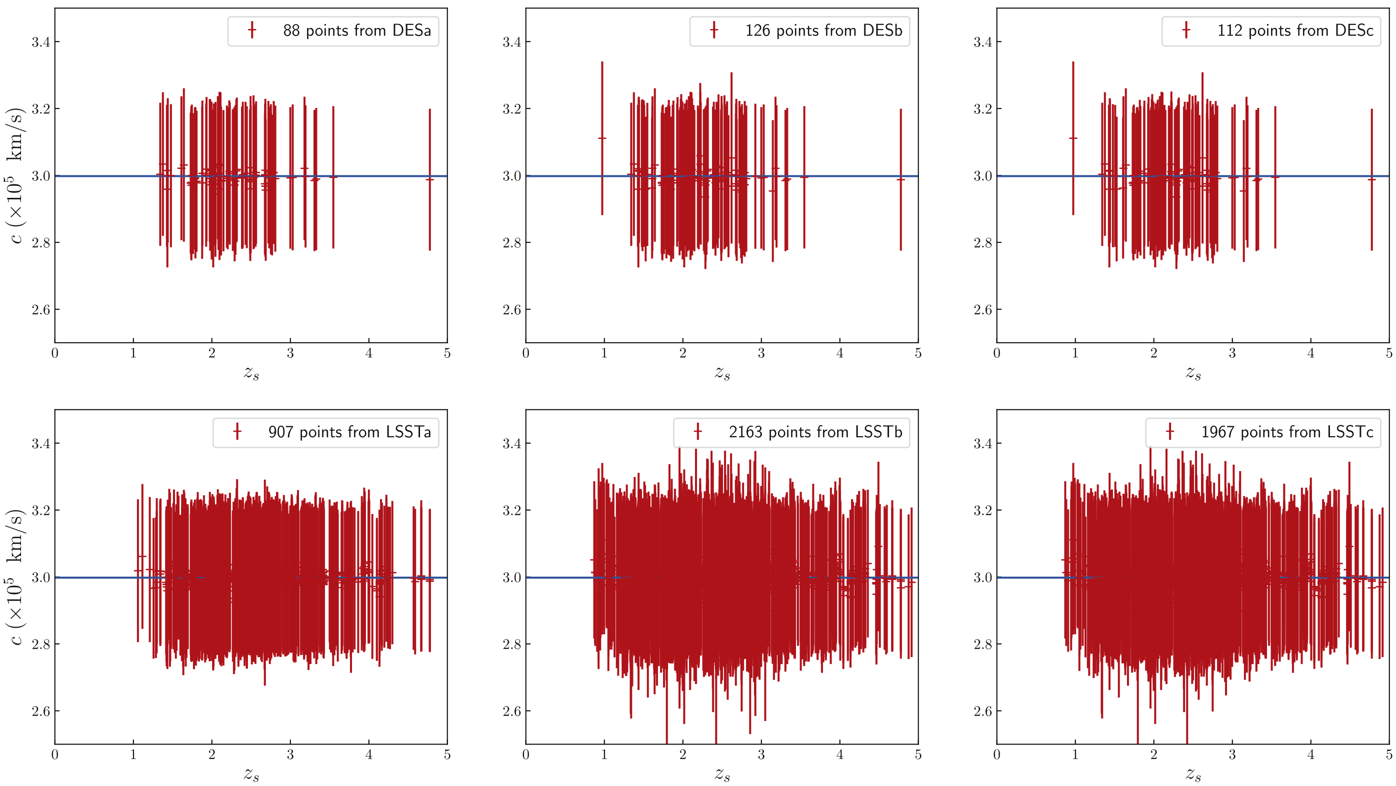

Figure 2. Individual measurements of the speed of light from forthcoming wide-area surveys: (a)—best single epoch, (b)—full stack, (c)—optimal stack imaging.

Table 1
Best-fit Values with 1σ Uncertainty for the Speed of Light Derived from Forthcoming Wide-area Surveys, with the Best Single Epoch, the Full and the Optimal Stack Imaging

Survey	DES (Best)	DES (Full)	DES (Optimal)
c (10^5 km s^{-1})	2.994 $\pm$ 0.016	2.995 $\pm$ 0.014	2.994 $\pm$ 0.015
Survey	LSST (best)	LSST (full)	LSST (optimal)
c (10^5 km s^{-1})	2.996 $\pm$ 0.004	2.995 $\pm$ 0.002	2.995 $\pm$ 0.003

galaxies, whose mass profiles are well approximated by singular isothermal ellipsoids (SIEs). Lens velocity dispersions are directly related to their masses. So in order to check how well our simulation represents real lenses we found that our simulated population of lenses is dominated by galaxies with $\sigma_{\rm ap} \approx 200$ km s^{-1}, having approximately Gaussian distributions characterized by $\sigma_{\rm ap} = 210 \pm 50$ km s^{-1}. Comparison of this result with the SL2S sample, also concerning the distribution of the Einstein radius in the population of lenses, reveals similarities between the simulations and the real observations.

Following the analysis of Collett (2015), we simulate three sets of realistic lensed quasars with different stacking strategies for combining multiple exposures (the best single epoch, the optimal and the full stack imaging), which takes into account the possibility that a deeper stacked image could be obtained with the combination of individual exposures for each object. When calculating the sampling distribution (number density) of lensed quasars expected for the baseline surveys, we adopt the differential rate of lensed quasar events as a function of z_s, based on the standard double power law for the quasar LF calibrated by strong-lensing effects (Oguri & Marshall 2010). As pointed out in the recent analysis by Collett & Cunnington (2016), the fractional uncertainty of the observed velocity dispersion and the Einstein radius is respectively determined at the level of 5% and 1%. Note, that although the line-of-sight contamination might introduce 3% uncertainties in the Einstein radii (Hilbert et al. 2009), this systematics might be reduced to the level of 1% in future strong-lensing surveys, which makes the assumption of 1% accuracy on the Einstein radius measurements reasonable. Recent analysis of the galactic-scale lens sample demonstrated that the total mass-density slope γ inside the Einstein radius can be determined with 1% (Wucknitz et al. 2004), which has been extensively applied in the literature (Cao et al. 2019; Qi et al. 2019b) and our simulations of quasar-galaxy lensing systems in this paper.

We also performed a Monte Carlo simulation to create mock "$\theta - z$" data including 500 intermediate-luminosity quasars covering the redshift range $0.50 \leqslant z \leqslant 6.00$. Construction of the mock catalog proceeded along the following steps. For the purpose of calculating the sampling distribution (number density) of quasars, we used their LF obtained from a combination of SDSS and 2dF (2SLAQ) surveys (Richards et al. 2005). Bright and faint end slopes in this double power-law LF agree very well with those in the bolometric LF at $z \sim 2$ according to Hopkins et al. (2007). In each simulation, we assumed that 500 intermediate-luminosity quasars will be detected by future VLBI surveys in the redshift range $0.50 \leqslant z \leqslant 6.00$. We further assumed that only 25 data points with redshifts $z > 4.50$ could be classified as targeted high-redshift quasars used in subsequent analysis. Fractional uncertainty of the angular size of compact structure "θ" was taken at a level of 3%. This is a reasonable assumption of "θ" measurements achievable in both current and future VLBI surveys based on better uv-coverage. This process was repeated

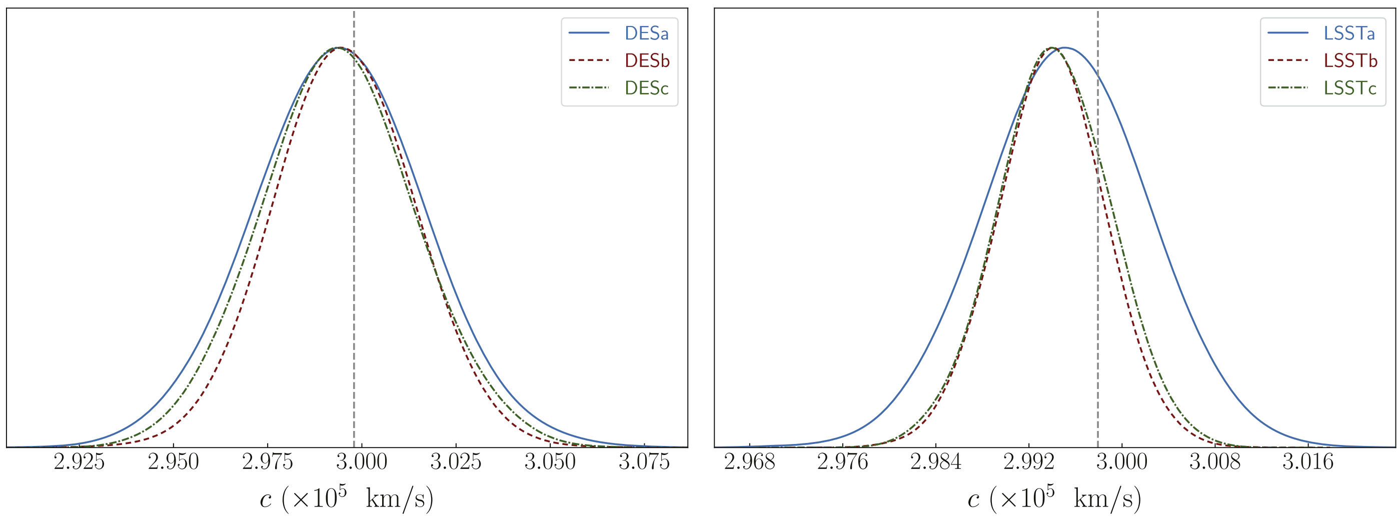

Figure 3. Probability distribution of the possible speed of light c obtainable from forthcoming wide-area surveys: (a)—best single epoch, (b)—full stack, (c)—optimal stack imaging.

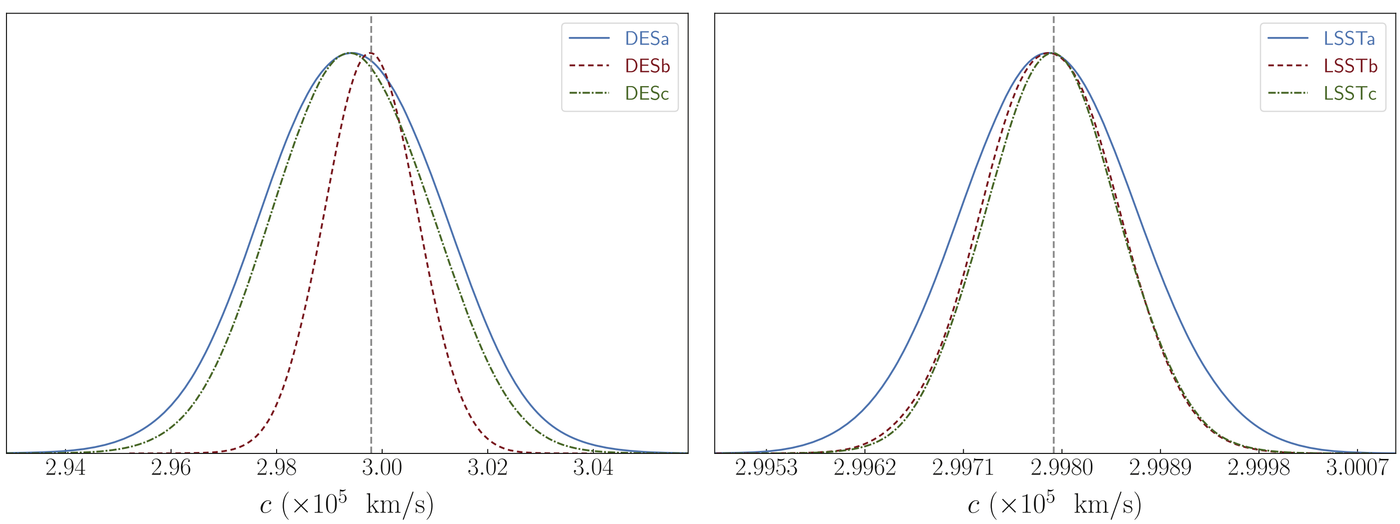

Figure 4. Probability distribution of the possible speed of light c obtainable from forthcoming wide-area surveys, with the profile of $\theta(z)$ reconstructed by GPs: (a)—best single epoch, (b)—full stack, (c)—optimal stack imaging.

100 times for each data set in order to guarantee unbiased final results.

In Figure 2 we illustrate the expected results of the speed of light measurements obtained from DES and LSST. Compared with the previous successful measurement of c engaging the quasar sample combined with the expansion rate function $H(z)$ (Cao et al. 2017a), concerning the method proposed here, the DES survey may provide $N \sim 90$ measurements of c for the best single epoch, $N \sim 120$ measurements of c for the optimal and the full stack imaging case. Moreover, we expect that the high-resolution imaging of LSST opens up the possibility of discovering a large number of strong-lensing systems leading to $N \sim 900$ measurements of c for the best single epoch, or $N \sim 2000$ measurements of c for the optimal and the full stack imaging case. The question now arises: are these measurements sufficient enough to detect possible VSL effects? Considering the high-precision measurement of the speed of light c_0 on Earth, with the fractional uncertainty of 10^{-9}, it is very difficult to achieve competitive results with cosmological measurements. Quasar observations, however, would provide us the value of c_{z_s}, the speed of light at redshift baseline z_s, from which we may study the accuracy concerning the deviation from c_0, $\Delta c = c_{z_s} - c_0$. The effectiveness of of our method could be seen from discussion of a second question: is it possible to achieve a stringent measurement of c in a cosmological setting while referring to the distant past? It is obvious that with so many measurements of c at different redshift baselines, we can obtain the statistical value of the speed of light. The forecasts for the DES survey are: $c = 2.994(\pm 0.016) \times 10^5$ km s^{-1}, $2.995(\pm 0.014) \times 10^5$ km s^{-1}, and $2.994(\pm 0.015) \times 10^5$ km s^{-1} with the best single epoch, the full and the optimal stack imaging, respectively. We have also explored whether there is any chance for LSST to perform better, and our results showed that enlarging the lens sample will make it possible to obtain more stringent constraints on the speed of light: $c = 2.996(\pm 0.004) \times 10^5$ km s^{-1} (best single epoch), $2.995(\pm 0.002) \times 10^5$ km s^{-1} (full stack), and $2.995(\pm 0.003) \times 10^5$ (optimal stack). Strongly lensed radio quasars observed by LSST would produce robust constraints on $\Delta c/c$ at the level of 10^{-4} if the compact structure measurements are available. More importantly, it is evident that in this case LSST may succeed at detecting VSL at the 1σ level while DES will fail at detecting VSL at the current observational level. These results are summarized in Figure 3 and in Table 1.

Note that there are many potential ways our technique might be improved. (I) One can use a powerful reconstruction method (Seikel et al. 2012) based on GPs to reconstruct the profile of $\theta(z)$, which makes it possible to make use of all strong-lensing data with redshifts (z_l and z_s) located in the redshift range of compact structure observations. "All" means not only these which are matched to radio sources in redshift, as proposed in this paper. Actually, the use of GPs will double the c measurements from future DES and LSST surveys, resulting in more stringent constraints on the speed of light. The results are shown in Figure 4. II. Our method could also extend to the galaxy–galaxy strong-lensing systems with high-redshift galaxies (not only quasars) acting as background sources. According to the analysis of Collett (2015), searches in DES and LSST data sets should discover 2400 and 120,000 galaxy–galaxy strong lenses, respectively. Such a significant increase of the number of strong-lensing systems will considerably improve the constraints on the speed of light. In this case, the measurement precision of c from cosmological measurements is expected to reach an accuracy attainable with laser interferometry at laboratories. Such accurate measurements of the speed of light could become milestones in precision cosmology.

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