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**Author:** Aleksandra Piórkowska, Marek Biesiada, Raphael Gavazzi

**Citation style:** Piórkowska Aleksandra, Biesiada Marek, Gavazzi Raphael. (2013). On the Complementarity of Different Cosmological Probes with SLACS, BELLS and SL2S Strong Gravitational Lensing Data. "Acta Physica Polonica B" (Vol. 44, no. 11 (2013), s. 2397-2404), doi 10.5506/APhysPolB.44.2397



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# ON THE COMPLEMENTARITY OF DIFFERENT COSMOLOGICAL PROBES WITH SLACS, BELLS AND SL2S STRONG GRAVITATIONAL LENSING DATA\*

ALEKSANDRA PIÓRKOWSKA, MAREK BIESIADA

Institute of Physics, Department of Astrophysics and Cosmology  
University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland

RAPHAËL GAVAZZI

Institut d'Astrophysique de Paris, UMR 7095, CNRS, UPMC  
Univ. Paris VI, 98 bis boulevard Arago, 75014 Paris, France

*(Received October 25, 2013)*

Accelerating expansion of the Universe is now an indisputable observational fact and became one of the most important issues of both physics and cosmology today, known as dark energy (DE) problem. The nature of this phenomenon is still unknown and from observational point of view the only way to put some light on cosmic expansion history is to combine different methods which are alternative to each other. In this light, we explore the idea that strong gravitational lensing systems offer new opportunity to constrain DE parameters in a way complementary to other cosmological probes. It turns out that the angle of the confidence contour major axis for strong lensing measurements depends on the redshift of the sample what may help to break the degeneracy in the  $w_0$ – $w_a$  parameters plane in the Chevalier–Polarski–Linder parametrization of DE equation of state.

DOI:10.5506/APhysPolB.44.2397

PACS numbers: 98.80.Es, 98.62.Sb

## 1. Introduction

The accelerating expansion of the Universe was firstly discovered at the end of the XX century on the type Ia supernovae (SNIa) Hubble diagrams [1] and then confirmed by independent estimates of the amount of baryons and cold dark matter [2]. Now, based on updated SNIa data [3] in comparison with precision measurements of cosmic microwave background radiation

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\* Presented by A. Piórkowska at the XXXVII International Conference of Theoretical Physics “Matter to the Deepest” Ustroń, Poland, September 1–6, 2013.

(CMBR) anisotropies [4] and baryon acoustic oscillations (BAO) imprinted in the large scale structure power spectrum [5], it is believed that this phenomenon is caused by the unknown form of energy providing the dominant contribution to the total energy budget of the Universe. One may need to consider modification of gravity at cosmological scales or some exotic material component (*e.g.* scalar field) to explain this puzzle. With lack of clear observational indications concerning the true nature of DE, a spatially flat [4] Friedman–Robertson–Walker model with the non-vanishing cosmological constant  $\Lambda$  and pressureless dark + baryonic matter became a standard reference point in modern cosmology. This so-called  $\Lambda$ CDM model, while strongly motivated by observations, suffers however from several problems of fundamental nature [6]. The essence of DE puzzle is that for this moment, there is no theoretical candidate substituting  $\Lambda$ . Whatever is the true mechanism lying behind this puzzle, any method providing alternative way of probing the cosmic expansion history is extremely important. In fact, one observational test (*e.g.* SNIa observations), even with good statistics and systematic precision, would not be sufficient if taken alone — the greatest accuracy in cosmological measurements can be achieved mainly via independent cross-checks and complementarity between alternative methods.

In this paper, we consider the possibility that strong gravitational lensing systems (as a cosmological tool) may help to constrain DE models in a way complementary to other methods.

## 2. Distance measures in cosmology

The possible way to describe the unknown DE is to consider it as a kind of non-standard barotropic component in hydrodynamical energy-momentum tensor with an effective equation of state  $p = w\rho$ . If one thinks of cosmic accelerating expansion as a phenomenon caused by some sort of a scalar field, it is very natural to expect that the  $w$  coefficient should vary in time, *i.e.*  $w = w(t)$ . This choice is strongly motivated by the fact that the only scalar field invoked by cosmologists — the inflaton — clearly had its own dynamics, since the inflationary epoch ended. An arbitrary function  $w(t)$  can be Taylor expanded over the scale factor  $a(t)$  (a real physical degree of freedom) and then translated to redshift, which in turn is an observable<sup>1</sup>. Bearing in mind that all recent cosmological surveys are able to probe only small and moderate redshifts, it is sufficient to explore first the linear order of the above expansion, known as the Chevalier–Polarski–Linder (CPL) parametrization  $w(z) = w_0 + \frac{z}{1+z}w_a$  [7]. Thus, the DE problem turns into a technical problem of determining the values of  $w_0$  and  $w_a$  parameters.

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<sup>1</sup> There is a unique correspondence between them:  $a(z) = (1+z)^{-1}$ .

One very direct cosmological probe is based on testing the distance-redshift relation  $D(z)$  (the so-called Hubble diagram when plotted). Of course, it can be done only if there is a possibility to determine distances and redshifts independently. In FRW geometry, a distance to an astrophysical object lying at redshift  $z$  is known as a co-moving distance  $r(z; \mathbf{p}) = c \int_0^z \frac{dz'}{H(z'; \mathbf{p})}$ , where  $H = \dot{a}(t)/a(t)$  is the cosmic expansion rate which depends on a variety of cosmological parameters (marked as  $\mathbf{p}$ ) like the so-called Hubble constant  $H_0$  (the present value of the cosmic expansion rate) and present energy density<sup>2</sup>  $\Omega_i, i \in m, r, X$  of respective components: matter, radiation and DE (*e.g.* DE parameters discussed above). However, we are not able to measure it directly. Instead, we have two observables based on clear observational concepts and strictly related to the co-moving distance (and to each other) via well defined Etherington reciprocity relation: the luminosity distance  $D_L(z; \mathbf{p}) = (1+z)r(z; \mathbf{p})$  and angular diameter distance  $D_A(z; \mathbf{p}) = \frac{1}{1+z}r(z; \mathbf{p})$ .

The luminosity distance is a measure invoked by using objects with known luminosity  $L$  (standard candles) according to the simple relation  $L = 4\pi D_L^2 F$ , provided that the flux  $F$  of the object and its redshift is measured. In cosmological context, the most important standard candles are SNIa but other astrophysical sources such as supernovae type II [8], gamma-ray bursts [9] or compact-object binaries emitting gravitational waves (the so-called standard sirens) [10] are also discussed.

Angular diameter distance can be obtained from  $R = D_A \theta$  for the standard rulers (*i.e.* objects whose size  $R$  is *a priori* known) if one can measure their angular scale  $\theta$ . These objects fall into two classes: statistical standard rulers (acoustic peaks in the CMBR anisotropy power spectrum, BAO) and individual standard rulers such as ultra compact radio sources [11], double-sided radio sources [12], and galaxy clusters [13].

### 3. Strong gravitational lenses as standard rulers

Recently, one can notice a growing interest in strong gravitational lensing measurements in the context of using them as standard rulers (it would be more appropriate to say “standard weights” since, in fact, the mass is standardized). This phenomenon occurs whenever the source (usually a quasar), the lens (galaxy) and the observer are aligned within the so-called Einstein ring. In this case, one can observe multiple images of the source. Angular size of this ring  $\theta_E$  defines a characteristic deflection scale of a given lens — this is the ruler of an individual lensing system which can

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<sup>2</sup> As a fraction of critical density.

be standardized. For the singular isothermal sphere (SIS) model<sup>3</sup> of the lens potential, Einstein radius  $\theta_E = \frac{4\pi}{c^2} \sigma_{\text{SIS}}^2 \frac{D_{\text{ls}}}{D_s}$  is a simple function of one-dimensional velocity dispersion of stars in lensing galaxy  $\sigma_{\text{SIS}}$  and the cosmological model (through the angular diameter distance to the lens  $D_l$  and between the lens and the source respectively  $D_{\text{ls}}$ ). One can easily notice that this ratio of (angular) distances can be used to constrain cosmological models  $D(z_l, z_s; \mathbf{p}) = \frac{D_s}{D_{\text{ls}}} = \frac{\int_0^{z_s} \frac{dz'}{h(z'; \mathbf{p})}}{\int_{z_l}^{z_s} \frac{dz'}{h(z'; \mathbf{p})}}$  provided that we have reliable knowledge about the lensing system: *i.e.* the Einstein radius  $\theta_E$  (from image astrometry) and stellar velocity dispersion  $\sigma_{\text{SIS}}$  (from central velocity dispersion  $\sigma_0$  obtained from spectroscopy [15]). This method is independent of the Hubble constant value (it gets cancelled in the distance ratio without producing any uncertainty to the final result) and is not affected by dust absorption or source evolutionary effects [15, 16]. It depends however on the reliability of lens model (*e.g.* SIS assumption) and, in particular, on the  $\sigma_0$  measurements<sup>4</sup>.

The use of strong lenses as standard rulers was investigated by [15] on simulated data. Later, Biesiada, Piórkowska and Malec firstly used this method in practice to constrain cosmological models in [20], and as a part of joint analysis together with SNIa, CMBR and BAO data in [21]. The results were generally in agreement with those obtained by other authors with different methods (see [22] for a comprehensive review).

#### 4. Complementarity of cosmological probes

In the context of determining the values of cosmological parameters, better statistics and systematics of observations is only a one side of a coin — there is a strong degeneracy in DE equation of state because  $w(z)$  overall should be negative. All well established methods of distance measures have the same fundamental dependence on  $w_0$  and  $w_a$  through the expansion rate (*i.e.* provide only anticorrelations between them). One should search for experiments developed specifically to overcome this problem as it has already been achieved for  $\Omega_m$  and  $\Omega_\Lambda$  parameters [3–5].

Hopefully, strong gravitational lensing systems may offer opportunity to break this impasse. Considering the distance ratio one can realize that this quantity provides different dependence on DE parameters than other cosmological data: a competition between two angular distances in the ratio may lead to positive correlations between  $w_0$  and  $w_a$ . This idea was firstly

<sup>3</sup> There is a growing evidence for homologous structure of early type galaxies [14] supporting reliability of SIS assumption.

<sup>4</sup> Hopefully, recent spectroscopic data for central parts of lens galaxies became available and they provide central velocity dispersions [17–19].

proposed by Linder in [23] and now we are considering it in more details. Following this line, we calculated the sensitivity of distance ratio for each of the DE parameter within CPL parametrization as a function of the lens redshift  $z_l$ , taking into account an idealized strong lensing system (with the most common case of  $z_s = 2z_l$ ), and  $\Lambda$ CDM as a fiducial model. Our results are shown in the left panel of Fig. 1. The larger is the absolute magnitude of distance ratio sensitivities at a particular redshift, the more constraining is our probe for the cosmological parameters. One can immediately notice that two curves in this figure, which represent sensitivity of distance ratio with respect to  $w_0$  and  $w_a$ , change their values from negative to positive on different redshifts. This suggests that there may be some redshift range (between  $z = 1.0$  and  $z = 1.7$ ) for which the distance ratio will give a positive correlations between CPL parameters. Consequently, a confidence contour in DE parameters plane for strong lensing data should change its position from parallel to the  $w_0$  axis at  $z \sim 1.0$  (no dependence on  $w_a$  coefficient) to the perpendicular one at  $z \sim 1.7$  (no dependence on  $w_0$ ). This situation is plotted in the right panel of Fig. 1 with marginalization over  $\Omega_m$  taken into account. Thus, careful selection of the strong lensing sub-samples according to the lens redshift makes it possible to achieve better accuracy on CPL parameters through the rotated degeneracy directions of these data sets.

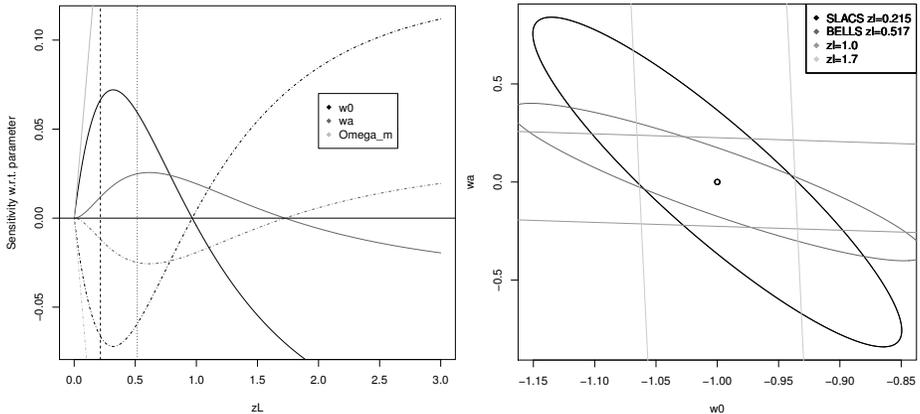


Fig. 1. Left panel: Sensitivity of the distance ratio to the cosmological parameters  $\Omega_m$ ,  $w_0$  and  $w_a$  as a function of the lens redshift. Solid lines correspond to our distance ratio, dash-dotted to the inverse of it which is sometimes discussed in the literature. Dashed black line perpendicular to the horizontal illustrates the position of the SLACS sample and the dotted one — median redshift of the BELLS sample. Right panel: Confidence contours for strong lensing measurements w.r.t. lens redshift calculated for SLACS and BELLS samples and for two hypothetical data sets lying on  $z = 1$  and  $z = 1.7$ .

Possible realization of this idea on real lensing data seems to be promising. As by now, we have two self-consistent data sets from: Sloan Lens ACS (SLACS) Survey [17] and BOSS Emission-Line Lens Survey (BELLS) [18] providing lenses lying at different median redshifts, so one can expect that for each sample there should be different sensitivity on the DE parameters. In fact, from the left panel of Fig. 1, we see that the SLACS sample is spread around the redshift  $z_{\text{SLACS}} = 0.215$  allowing the data to be more sensitive to  $w_0$  parameter while the mean redshift of the BELLS sample ( $z_{\text{BELLS}} = 0.517$ ) makes its distance ratio to be more affected by  $w_a$  parameter. This coincidence makes it clear why, with a rather poor sample of strong lensing data ( $n = 20$  lenses), we were able to constrain cosmological parameters and perform a joint analysis leading to reasonable results comparable to those obtained in using other methods of distance measures [21]. Recently, an increasing number of data from strong lensing systems discovered as a part of Strong Lensing Legacy Survey (SL2S) [19] and consisting of lenses spanning the redshift range  $z = 0.2\text{--}0.8$  are expected to complement SLACS and BELLS measurements.

One may ask about the complementarity of strong lensing measurements with other cosmological probes. In this context, we analyse SNIa data as representative for classical distance measures. In the left panel of Fig. 2, we see that SNIa reveal similar behaviour of degeneracy direction with redshift as in strong lensing measurements: the farther is the redshift of the object, the more constrained is the  $w_a$  coefficient while the information about  $w_0$

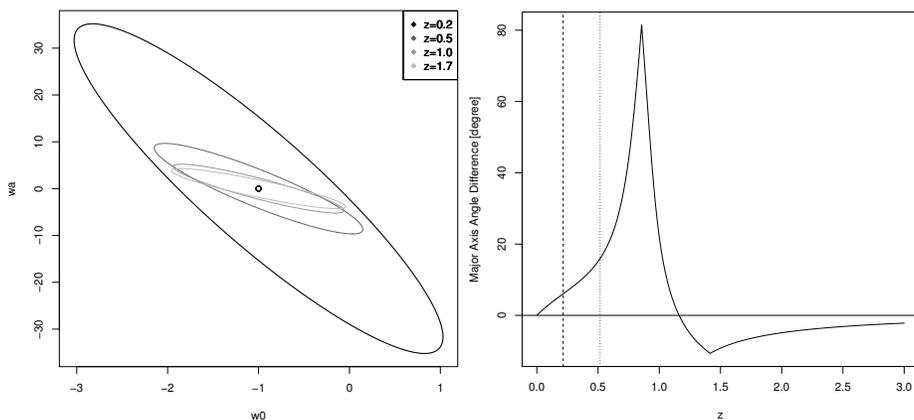


Fig. 2. Left panel: Confidence contours for SNIa measurements w.r.t. redshift for the same redshifts as in Fig. 1 for better comparison of results. Right panel: Difference between major axis angles of the confidence contours for strong lensing and SNIa measurements as a function of the redshift. The lines perpendicular to the horizontal axis are the same as on the right panel of Fig. 1.

value is wasted. One can notice that the rotation is a bit slower for supernovae data, so there may be some redshifts for which carefully selected sub-sample of SNIa data may complement respective sub-sample of strong lensing measurements. To check this possibility, we calculated the difference between major axis angles of confidence contours for strong lensing and SNIa measurements as a function of the redshift (plotted on the right panel of Fig. 2). At this point, we can make a following conclusion: using distance ratios we never gain full perpendicularity — the difference between degeneracy directions is highly limited — but for the redshifts up to  $z = 1$  strong lensing data offer valuable tool to other cosmological observations.

## 5. Conclusions

In this paper, we presented our results considering the idea, proposed previously by Linder [23], that distance ratio from strong lensing measurements offers an opportunity to break the strong degeneracy between DE parameters. We have shown that one can use the cross-checks between carefully selected data according to the redshift of the lensing galaxy (*e.g.* between SLACS and BELLS samples) to pin down the values of cosmological parameters in CPL parametrization. In this context, the ongoing surveys such as CLASS, SLACS, SL2S, SQLS, HAGGLEs, AEGIS, COSMOS and CASSOWARY are promising for providing an increasing number of discovered strong lensing systems with accurate spectroscopic and astrometric data. We also expect, that new projects (Pan-STARRS1, LSST2, JDEM/IDECS3, SKA4) will provide a great number of strong lensing data suitable for our purpose. Our method relies on the prior knowledge of mass profile usually assumed to be SIS, which is supported by SLACS data. However, it should be noticed that there is a growing evidence that the slope of the mass density profile in lensing galaxies evolves with redshift — see *e.g.* recent papers by Sonnenfeld *et al.* [19]. Work on how to address this issue within our method is in progress.

This work was carried out within the framework of the European Associated Laboratory “Astrophysics Poland–France” HECOLS.

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