Strong Gravitational Lensing in the Era of Big Data
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The last stand before Rubin: semi-automated inverse modelling of galaxy-galaxy strong lensing systems

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Abstract. Galaxy-galaxy strong lensing (SL) systems provide a unique opportunity to test modified gravity theories. Deviations from General Relativity are encoded in the post-Newtonian parameter (γ). As a preparation for the upcoming data from the Vera Rubin Observatory Legacy Survey of Space and Time (LSST), our research group collected imaging data of SL systems from ground-based telescopes and conducted spectroscopic observations of 21 systems on the Southern Astrophysical Research (SOAR) Telescope to measure the lens velocity dispersions, σ_v. We briefly describe the semi-automated SL modelling of the systems in this sample and combine the results with σ_v from SOAR to derive an estimate for γ. Our preliminary results yield a value of $\gamma = 1.17^{+0.29}_{-0.33}$, which is consistent with General Relativity. Although the error bars are limited by the sample size, this result represents the first constraint on modified gravity obtained purely from ground-based data, with a sample completely independent from previous studies, and which allows for a self consistent end-to-end analysis.

Keywords. gravitational lensing: strong - methods: data analysis - galaxies: structure - techniques: spectroscopic

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1. SOAR sample for measuring the γ post-Newtonian parameter

Previous studies have used galaxy-galaxy strongly lensed systems (aka "Einstein rings") to set constraints on the post-Newtonian parameter γ, which is essentially the ratio between the two scalar potentials that appear in the space-time metric at the linear level (the so-called Newtonian and curvature potentials). This ratio can be constrained by comparing the trajectories of massless bodies (photons), probed by gravitational lensing, to the motion of non-relativistic particles, probed by the stellar dynamics. The first is sensitive to the sum of the potentials, while the second is sensitive only to the Newtonian

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potential. Therefore, by comparing lensing mass reconstructions to the stellar velocity dispersion in galaxies one is able to set constraints on γ (see Schwab, Bolton, and Rappaport (2009), Cao et al. (2016), Liu et al. (2022)). While the most recent studies contain over 150 systems, all previous estimates of γ build up over the previous samples (i.e. they all share a common set of systems). Furthermore the vast majority of the systems are modelled from space-based (i.g. HST) data, from surveys such as SLACS (Auger et al. 2010) and BELLS (Bolton et al. 2012) (see also Shajib et al. (2021), Etherington et al. (2021)). Typically, the systems from these samples have velocity dispersions from Sloan Digital Survey (SDSS) spectroscopic data.

In this work, we are interested in using systems that are modelled directly from ground-based images, as expected in the future from LSST. To this end our group has carried out an extensive compilation of systems in the footprint to the current ground-based wide-field imaging surveys that achieve typical resolutions around 1 arcsecond or better. This sample includes, but is not limited to, imaging data from the Survey of Gravitationally-lensed Objects in HSC Imaging (SuGOHI), Dark Energy Survey (DES), Kilo-Degree Survey (KiDS), and the Legacy Survey. This sample contains over 30,000 candidate gravitational lens systems, among which a few hundred are expected to be suitable for modelling. A detailed description of this dataset will be presented in Oliveira et al., in prep. We refer to this comprehensive compilation of gravitational lenses as "The Last Stand Before Rubin" (LaStBeRu).

With the aim of inferring the post-Newtonian parameter, we focused on obtaining good estimates of the line-of-sight velocity dispersion σ_v for Einstein rings selected from the LaStBeRu sample, thus building a new dataset for measuring γ. We selected systems which had source and lens redshifts available from the literature and whose lens galaxies were bright enough to yield spectra with† $S/N \sim 10 - 20$ (in a 4-m class telescope), to allow for a good determinations of σ_v. We visually inspected all systems that passed our cut to select those we expected to enable a good strong lensing modelling from the ground based data. Finally, we required good observability conditions from the south. Our selected sample was observed with the Goodman high throughput spectrograph in single slit mode on the SOAR telescope. Our sample contains 21 systems with σ_v determined using the pPXF method on the reduced SOAR spectra.

2. Modelling results and modified gravity constraints

To model the imaging data from the 21 lensing systems, we initiated the analysis by deriving noise maps and point-spread functions (PSFs). Noise maps are estimated from the background levels of the images. With the recovered background values, we scaled the original image according to the inverse of the effective gain, which is determined by the product of gain, the number of combined images, and exposure time. For the PSFs, we identified the astronomical objects in the wide-field images using the SExtractor software, selecting star candidates by applying a cutoff of 0.8 on the stellarity parameter. From the resulting objects, we selected the stars closest to the gravitational lens and applied the interactive PSFr reduction pipeline (Birrer et al., in prep.), which utilizes features from lenstronomy (Birrer et al. 2021).

The lensing systems are modelled using an updated version of the Source Lens And Mass (SLAM) pipeline (which builds up upon Etherington et al. (2021)), where, by default, the lens light brightness is fitted concurrently with the lens mass and source brightness. The method begins by parametrically fitting the source to provide an initial estimate of the modelling. Next, we fits the source using a non-uniform distribution of pixels and re-fit the lens brightness. We finalize the pipeline by fitting a

† Ideally, we want to achieve a higher signal-to-noise ratio than SDSS (Sloan Digital Sky Survey) because σ_v dominates the balance of statistical error in γ.

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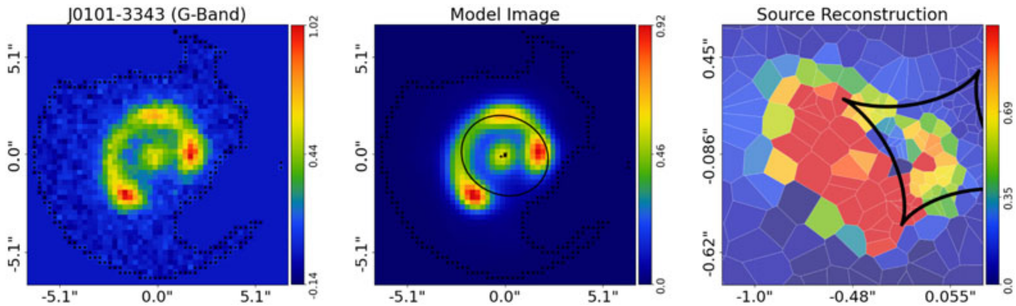

Figure 1. Modelling results for system J0101-3343. Left: g-band imaging data from DES used for the modelling. Middle: reconstructed image. The black curve shows the critical line. Right: zoomed-in reconstruction of the source plane. The black curve shows the caustic.

power-law mass profile. These steps were implemented using features from PyAutoLens (Nightingale, Dye, and Massey 2018; Nightingale et al. 2021). If the light distribution of the system is complex, for instance, due to the presence of nearby galaxies or blending of the arc with other sources, we employ an interactive extraction method that utilizes segmentation maps generated via SExtractor to create masks for removing the unwanted sources. We show in Fig. 1 an example of the modelling results for object J0101-3343.

Combining the results from our modelling on the 21 systems with the velocity dispersions obtained from the SOAR data and following the same methodology as in Cao et al. (2016) we were able to derive a first estimate of the post-Newtonian parameter: $\gamma = 1.17^{+0.29}_{-0.33}$. In General Relativity $\gamma = 1$, which is consistent with our results at the 68% confidence level. Although the error bars are significantly larger than the current estimates in the literature, to the best of our knowledge, this is the first result using a sample of systems that is completely independent from the one used in previous works. More importantly, these results show the potential for using ground based data to test gravity. Furthermore, the current data allows for a self consistent end-to-end analysis of the data, without the need to set strong global priors on the mass and light distribution of the lenses, as is usually done, and enabling us to consider the effect of the PSF on a system-by-system basis. Such analysis is expected to be less prone to systematics and will be explored in forthcoming studies.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1743921323004222.

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