Cluster strong lensing: a new strategy for testing cosmology with simulations

M. Killedar[1,2], S. Borgani[2], D. Fabjan[3], K. Dolag[1,4], G. Granato[2], M. Meneghetti[5] S. Planelles[2] & C. Ragone-Figueroa[6]

Second Bayesian Young Statisticians Meeting (BAYSM 2014)
Vienna, September 18–19, 2014

[1] Universitäts-Sternwarte München, München, Germany
killedar,dolag@usm.lmu.de

[2] Dipartimento di Fisica dell'Università di Trieste, Sezione di Astronomia, Trieste, Italy
killedar,borgani,granato,susana.planelles@oats.inaf.it

[3] SPACE-SI, Slovenian Centre of Excellence for Space Sciences and Technologies, Ljubljana, Slovenia
dunja.fabjan@space.si

[4] Max-Planck-Institut für Astrophysik, Garching, Germany
kdolag@mpa-garching.mpg.de

[5] INAF - Osservatorio Astronomico di Bologna, Bologna, Italy
massimo.meneghetti@gmail.com

[6] Observatorio Astronómico, Universidad Nacional de Córdoba, Córdoba, Argentina
cinthia.ragone@gmail.com

Abstract

Strong lensing properties of galaxy clusters have been routinely used to claim either tension or consistency with ΛCDM cosmology. However, standard approaches are unable to quantify the preference for one cosmology over another. We advocate a Bayesian approach whereby the parameters of the strong lensing-mass scaling relation, α and β, are treated as the observables. We demonstrate a method of estimating the likelihood for observing α and β under the ΛCDM framework, using the X-ray selected $z > 0.5$ MACS clusters as a case in point and employing hydrodynamic simulations. We account for mock sample variation due triaxiality within the modelling of the likelihood function. Cluster selection and characterisation of lensing are found to play as important a role as the uncertainty surrounding feedback.

Keywords: gravitational lensing; galaxy clusters; statistics

1 Introduction

Galaxy clusters gravitationally lens and distort the images of background galaxies; their lensing efficiency is a powerful probe of cosmology with the ability to constrain the aforementioned structure formation parameters [1]. The earliest comparisons between simulated clusters and the observed frequency of arc-like lensed galaxy images in a cluster sample revealed an order of magnitude difference between the observations and

ΛCDM predictions [1, 4]. This discrepancy, dubbed the 'arc-statistics problem', has the potential to be a point of tension for the standard ΛCDM model.

In the present work, we propose a Bayesian approach to the cosmological test using strong lensing properties of this sample, and clusters modelled within hydrodynamic simulations which include the effects of stellar and AGN feedback. Cluster selection criteria and characterisation of strong lensing efficiency affects the result of the comparison, so this is explored here.

2 Section

Strong lensing efficiencies, as characterised by the Einstein radii, scale well with the mass of clusters at large overdensities [3]. If the $z > 0.5$ MACS sample are, in fact, stronger lenses than predicted by the ΛCDM model, they will have larger Einstein radii for a given total mass at low overdensities (or a proxy thereof).

A Bayesian approach is advocated, in which one determines the relative preference of two hypothetical cosmological models, C_1 and C_2, in light of the data D, by calculating the Bayes factor B:

$$B = \frac{\mathcal{L}(D|C_1)}{\mathcal{L}(D|C_2)} \tag{1}$$

where $\mathcal{L}$ denotes the likelihood of the data assuming a cosmology. The aim is to calculate the likelihood of observing the Einstein radii of the high-z MACS sample under one chosen hypothesis: ΛCDM, with the aid of numerical simulations.

This is non-trivial, as one cannot simply construct a likelihood function related to the observables (θ_E and M_{500}) because there are a finite number of objects from the simulations. Instead, we assume a power-law relation between the strong lensing and mass proxies, and perform a fitting to the following function in logarithmic space:

$$\log\left[\frac{M_{500}}{9\times10^{14}M_\odot}\right] = \alpha\log\left[\frac{\theta_E}{20"}\sqrt{\frac{D_d}{D_{ds}}}\right] + \beta \tag{2}$$

with parameters (α and β) and aim to find the likelihood of observing *the scaling relationship.*

The pivot mass $9\times10^{14}M_\odot$ is chosen to approximate the logarithmic average of the observed and simulated clusters. Similarly the pivot Einstein radius is chosen to be 20 arcseconds. We also acknowledge that there is likely to be intrinsic scatter in this relationship directly comparable to the scatter in the concentration-mass relation, partly due to cluster triaxiality and substructure and partly from the varying formation histories of the clusters. Thus we also include a nuisance parameter, V, which represents intrinsic Gaussian variance, orthogonal to the line. We employ the linear regression method outlined in[2].

In the left panel of Fig. 1 we show the relation between the Einstein radii and the cluster mass M_{500}. The $z > 0.5$ MACS sample are represented by red circles. For simulated clusters, the situation is more complicated. Since different lines of sight provide a large variation in projected mass distribution, each cluster cannot be associated with an individual Einstein radius, nor a simple Gaussian or log-normal distribution [3]. We therefore measure the Einstein radius for 80 different lines of sight and, for ease of visualisation, describe the distribution of Einstein radii for each simulated cluster by a box-plot[1].

[1] In the box-plots, we mark the median with a short black horizontal line, a blue box marking the

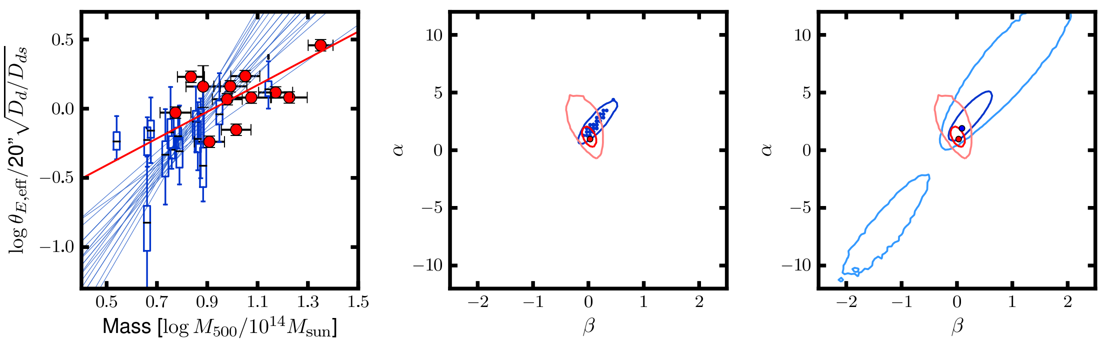

Figure 1: Einstein radii statistics for $z = 0.5$ clusters from the AGN simulations. *Left*: Strong lensing efficiency, characterised by scaled Einstein radii, $\theta_{\mathrm{E,eff}}$, plotted as a function of mass. The range of Einstein radii for simulated clusters are shown by the blue box-plots. The red circles represent the MACS $z > 0.5$ clusters. The red line marks the maximum a-posteriori fit to observational data, while the thin blue lines mark the fit to 20 randomly chosen mock samples from simulations. *Middle*: 1-σ and 2-σ constraints on parameters of the strong lensing - mass relation given the MACS $z > 0.5$ cluster data (red contours), with a maximum a posteriori fit marked by a red circle. Overplotted in blue dots are the best fits to 80 mock observations of $z = 0.5$ clusters from the AGN simulations. A typical 1-σ error is shown as a blue ellipse. *Right*: Same as the middle panel, but the blue circle and curves mark respectively the maximum and the 1-σ and 2-σ contours of the likelihood function found by combining all 80 mocks. Ultimately, the likelihood, $\mathcal{L} = 0.31$, is found by convolving the functions marked by the red and blue contours

We fit the observational data to the lensing-mass relation and after marginalising out the nuisance parameter, V, present the posterior distribution for α and β, denoted by red contours in the middle panel of Fig. 1. This fit is re-interpreted as a single 'data-point'. To estimate the likelihood, *as a function of possible data*, we employ the simulations. Many mock samples are individually fit to the lensing-mass relations; the maximum of the posterior is shown as a blue point and a typical 1-σ error shown as a blue ellipse. By adding the posteriors for each mock sample and renormalising, we estimate the required likelihood function, shown by the blue contours in the right-hand panel of Fig. 1. By multiplying by the 'data-point' distribution and integrating over the parameter space, we find $\mathcal{L} = 0.31$.

Note that one cannot comment on whether the likelihood is *large* or *small*. However, if the same process is repeated for simulations under a different cosmological model then the Bayes factor can be calculated and, after accounting for priors, may (or may not) reveal a preference for one of the cosmologies, in light of this data.

References

[1] Bartelmann, M. and Huss, A. and Colberg, J. M. and Jenkins, A. and Pearce, F. R., (1998) "Arc statistics with realistic cluster potentials. IV. Clusters in different cosmologies" A&A, **330** 1–9

[2] Hogg, D. W. and Bovy, J. and Lang, D. (2010), ArXiv: 1008.4686

[3] Killedar, M. and Borgani, S. and Meneghetti, M. and Dolag, K. and Fabjan, D. and Tornatore, L. (2012) "How baryonic processes affect strong lensing properties of simulated galaxy clusters", MNRAS, **427** 533-549

[4] Li, G.-L. and Mao, S. and Jing, Y. P. and Bartelmann, M. and Kang, X. and Meneghetti, M. (2005), "Is the Number of Giant Arcs in ΛCDM Consistent with Observations?", ApJ, **635** 795-805

25th and 75th percentiles and stems to meet the furthest datapoints within 1.5 times the inter-quartile range