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A new strong-lensing model for the massive galaxy cluster PLCKG287.0+32.9

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Summary. — We present a new high-precision strong lensing model of PLCK G287.0+32.9, a massive lens galaxy cluster at $z = 0.383$, based on 153 spectroscopically and photometrically selected member galaxies and 47 secure multiple images of 12 background multiply-lensed sources. The total mass distribution derived from our model shows this cluster to be a very prominent gravitational lens with the third biggest Einstein radius of $\theta_E = 43.4'' \pm 0.1''$ known to date.

1. – Introduction

Strong gravitational lensing gained a more and more central role in validating the predictions of cosmological models, such as the standard Λ Cold Dark Matter (Λ-CDM). For instance, the comparisons between the predictions of cosmological simulations and the distribution of cluster total masses derived from lens models have suggested that the hierarchical formation of large-scale structure may not follow the Λ-CDM model due to, for example, incorrect assumptions about the properties of dark matter [1-4]. Similarly, the observed distribution of the effective Einstein radius θ_{E} of galaxy clusters [5], the radius of the area enclosed within the critical curve of infinite magnification if it were a circle, may be in tension with theoretical predictions of Λ-CDM [6, 7] and, in this context, the number of rare massive clusters can be used as a constraint to test whether

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this tension is real or not. In particular, the theoretical total all-sky count of galaxy clusters with $\theta_{\mathrm{E}} \geq 40''$ is expected to be $\sim 8 \pm 3$ [5] and, to date, only a handful of clusters have been confirmed to have a such large Einstein radius [8-11].

Among these peculiar objects, the galaxy cluster PLCK G287.0+32.9 (PLCK-G287 hereafter) stands out, being the second most significant Sunyaev-Zel'dovich detection from the Planck catalog [12]. Previous studies highlighted a complex structure indicating a massive post-merger system [13-15] at redshift $z_c = 0.383$. A first strong lensing model, based on solely photometric data, found PLCK-G287 to have a very large Einstein radius of $\theta_{\mathrm{E}} = 42'' \pm 4''$ and a total mass enclosed within the corresponding critical curve of $(3.1{\pm}0.5){\times}10^{14} M_{\odot}$ [16]. However, at the non-linear tail of the Einstein radii distribution, a 10% uncertainty can make the difference between a somewhat normal cluster and a very peculiar object which in principle can be used to challenge the predictions of the Λ-CDM model. Our study aims to develop a new precise strong lensing model for this cluster, taking advantage of a new extensive spectroscopic campaign.

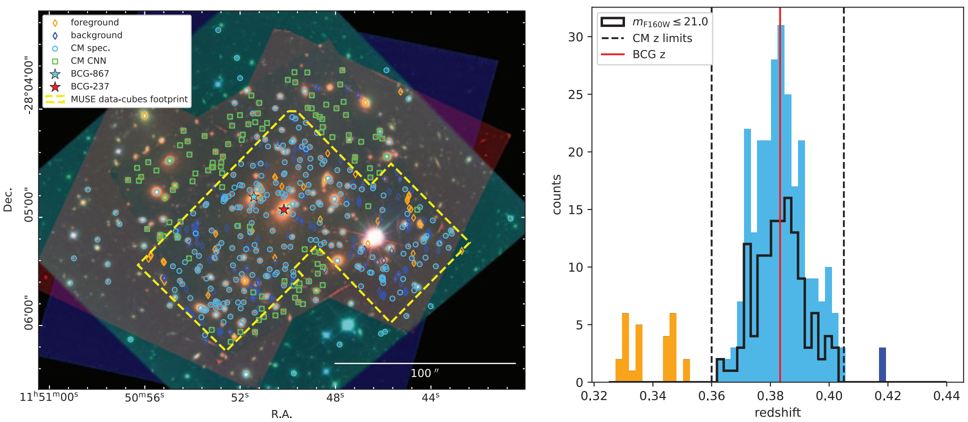
2. – The lens model

The combination of multi-band imaging obtained with the Hubble Space Telescope (HST), part of the Reionization Lensing Cluster Survey (RELICS [17], P.I.: Dan Coe, program ID 14096; HST observation cycle 23 P.I.: Seitz, program ID 14165), and new high-quality spectroscopic observations carried-out with the Multi-Unit Spectroscopic Explorer (MUSE, P.I.: Amata Mercurio, ESO program 0102.A-0640(A)) allows us to build a spectroscopic catalog containing secure redshift measurements for 432 sources. We complete this catalog with redshift measurements from observations made with the VIsible MultiObject Spectrograph (VIMOS, P.I.: Mario Nonino, period 094.A-0529(B), 11 objects) and DEep Imaging Multi-Object Spectrograph (DEIMOS, 47 objects) [18,19]. We identify a total of 153 cluster member galaxies with $m_{\mathrm{F160W}} \leq 21$: 129 spectroscopic ones in the redshift range [0.360, 0.405], in addition to 24 photometric ones identified using a Convolutional Neural Network technique [20] applied to HST imaging data (see fig. 1). We use this magnitude threshold to reduce the complexity of the model and, therefore, the computation time. Using the MUSE spectroscopic data we also identify 114 multiple images of 28 background sources, of which 84 images from 16 are new and the remaining ones were identified in previous work [21]. From these, we select a sample of 47 secure multiple images of 12 background sources that cover a wide redshift range, from $z = 1.17$ to $z = 5.39$.

We use the software lenstool [22-24] to model the total mass distribution of PLCK-G287 as a sum of several components that take into account the contribution of a) the cluster members, b) one or two BCGs that are parameterized separately from the other members, c) the cluster-scale halos, and d) a constant convergence or shear introduced by possible unaccounted lensing effects. A detailed description of the data analysis and the strong lensing model can be found in our recent publication "The powerful lens galaxy cluster PLCK G287.0+32.9 ($\theta_{\mathrm{E}} \sim 43''$)" [25]

3. – Results and discussion

We test several configurations and for each one we computed the root mean square of the separation between the observed position $\boldsymbol{x}_i^{obs}$ and predicted one $\boldsymbol{x}_i^{pred}$ of the N_{im}^{tot}



(a) (b)

Fig. 1. – (a) RGB image of the galaxy cluster PLCK-G287 obtained by combining the HST images (red: F105W, F110W F125W, F140W F160W; green: F814W; blue: F435W, F475W, F606W). The yellow dashed line indicates the area covered by the MUSE observations. The cyan circles and green squares indicate, respectively, spectroscopic and CNN-identified cluster members, while the orange and blue diamonds indicate, respectively, spectroscopic foreground and background objects. The two BCGs that have been modeled independently of the other members are indicated by the red and cyan stars. (b) Redshift distribution of objects in the HST footprint, zoomed around the redshift of the BCG ($z_c = 0.383$, solid red line) and the thresholds used to select cluster members ($0.360 \le z \le 0.405$, dashed lines). The solid black line shows the distribution of members with F160W Kron magnitude values ≤ 21.

multiple images, defined as (1)

$$\Delta_{RMS} = \sqrt{\frac{1}{N_{im}^{tot}} \sum_{i=1}^{N_{im}^{tot}} \left|\left|\boldsymbol{x}_i^{pred} - \boldsymbol{x}_i^{obs}\right|\right|^2}. \tag{1}$$

We find that the best-fitting configuration is the one with 3 cluster-scale halos, with two BCGs, and without the external convergence-shear component. The corresponding $\Delta_{RMS} = 0.75''$ improves by a factor 2.5 the accuracy of reconstructing the position of multiple images, with respect to the previous model [21]. Our model reveals a mass distribution that is slightly elongated along the NW-SE direction, which is compatible with the post-merger scenario suggested by previous studies [13, 14, 26]. The analysis of the predicted total mass distribution confirms PLCK-G287 to be a prominent gravitational lens with an Einstein radius of $\theta_{\rm E} = 43.4'' \pm 0.1''$, the third largest after MACS J0717.5+3745 [8] and Abell 1689 [10], and a total mass enclosed within $\theta_{\rm E}$ of $3.33^{+0.02}_{-0.07} \times 10^{14} M_\odot$. The Λ-CDM model predicts a total all-sky count of only $\sim 8 \pm 3$ galaxy clusters with $\theta_{\rm E} \ge 40''$ [5] therefore systems such as PLCK-G287, are of particular interest for their leverage on predictions of the Λ-CDM model.

Thanks to the predictive power of our model, we discover three new multiple images that were not previously identified, corroborating thus the goodness of our strong lens modeling. We are also able to reconstruct the complex configuration of three background sources, that were not used for the model optimization due to the uncertainty of the redshift measurements, obtaining redshift estimations that are consistent with the photometric ones available in literature [21].

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