

The Central Mass Distribution of the Lensing Cluster SDSS J1004+4112

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The cluster SDSS J1004+4112 represents a rare example of a quasar lensed by a massive foreground cluster of galaxies, which was discovered in 2003 from the Sloan Digital Sky Survey data[1]. It consists of five images of a quasar at $z = 1.734$ produced by a cluster at $z = 0.68$. In addition, several background galaxies at $z = 2-3$ are also found to form multiple images (see Fig. 1).

Here we analyzed image configurations of many multiple images and time delays between quasar images to explore the central mass distribution of the cluster in details[2]. For this purpose, we developed a new lensing software called *glafic*, which implements the fast lens equation solver and several optimization methods to derive best-fit mass models.

Fig. 1 shows the best-fit mass model. The model successfully reproduces all the image configurations as well as time delays between quasar images. In the model the center of the dark matter distribution agrees well with the position of the central galaxy, in marked contrast to some of previous modeling of this system in which the offset between the dark matter center and central galaxy has been reported. Fig. 2 indicates that the radial mass distribution also shows an excellent agreement with the mass distribution inferred from *Chandra* X-ray observation[3].

The result suggests that the cluster is highly relaxed system which have formed in the early universe. In contrast, the standard structure formation model predicts that high-redshift clusters, as explored above, tend to be unrelaxed. The existence of such relaxed cluster already at $z = 0.68$ therefore should be confronted with numerical simulations.

Note that the lensing software *glafic* presented above is publicly available at <http://www.slac.stanford.edu/~oguri/glafic/>

References

- [1] Inada, N., et al.: 2003, *Nature*, **426**, 810.
- [2] Oguri, M.: 2010, *PASJ*, **62**, 1017.
- [3] Ota, N., et al.: 2006, *ApJ*, **647**, 215.

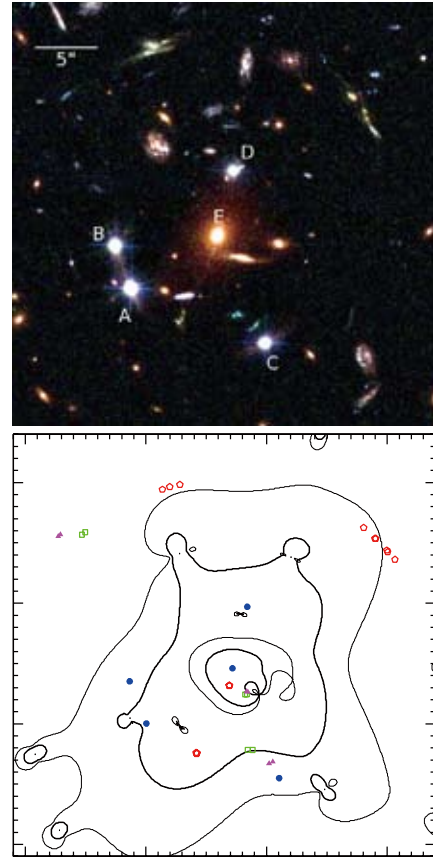


Figure 1: Top: *Hubble Space Telescope* image of SDSS J1004+4112, with quasar images indicated by A-E. Bottom: Critical curves for $z = 1.734$ (thick) and $z = 3.33$ (thin) obtained for the best-fit mass model.

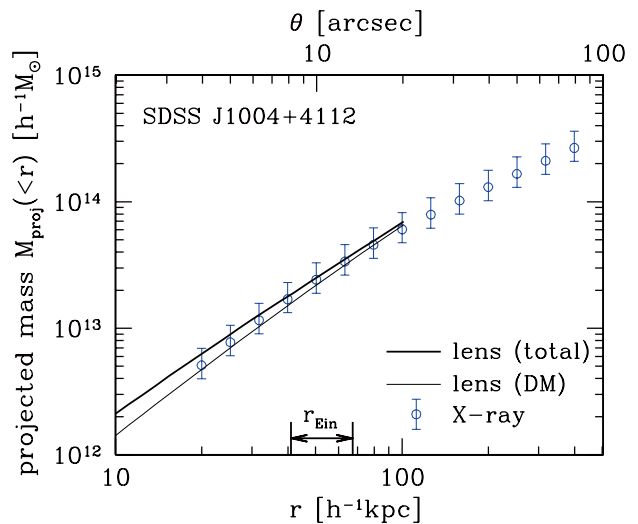


Figure 2: The radial mass distribution inferred from lensing analysis is compared with *Chandra* X-ray result.