

## Strong Lensing Constraints on the Properties of Cluster Galaxies

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A recently discovered quadruply-imaged QSO, SDSS J1004+4112 (Inada et al. 2003; Oguri et al. 2004) in the core of a  $z = 0.68$  galaxy cluster has an unprecedented image separation of  $\sim 13''$ . This lens gives us a unique opportunity to study the detailed mass distribution in the central regions of this cluster. We present free-form reconstructions of the lens using recently developed methods. The projected mass within 100 kpc is well-constrained as  $5 \pm 1 \times 10^{13} M_{\odot}$ , consistent with previous simpler models. Unlike previous work, however, we are able to detect structures in the lens associated with cluster galaxies. We estimate the mass associated with these galaxies, and show that they contribute not more than about 10% of the total cluster mass within 100 kpc. Typical galaxy masses, combined with typical luminosities yield a rough estimate of their mass-to-light ratio, which is  $\lesssim 10$ , implying that these galaxies consist mostly of stars, and possess little dark matter.

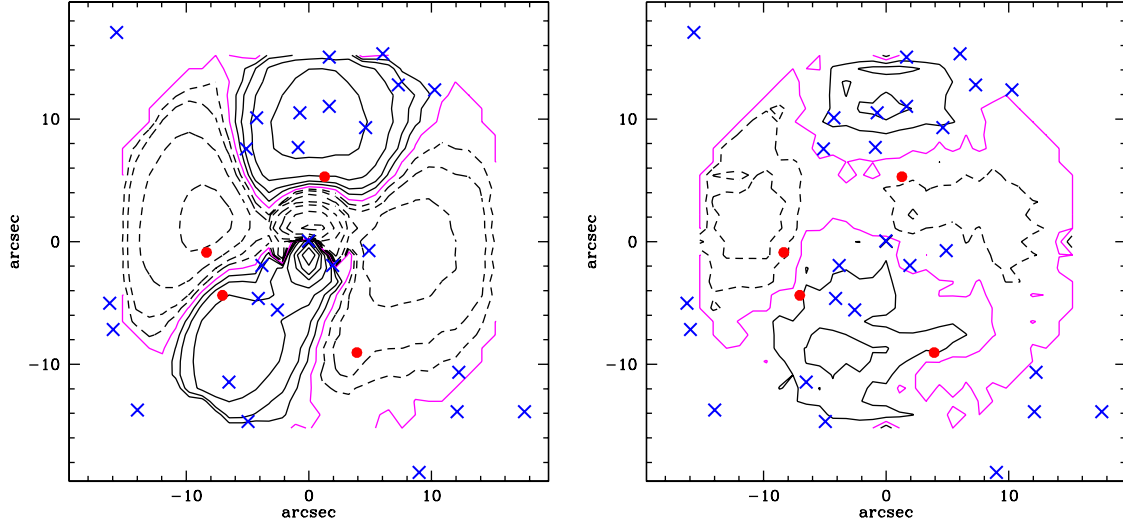
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**Figure 1: Residual mass maps** obtained by subtracting the circularly averaged mass distribution from *PixeLens* ensemble average maps. The solid black contours indicate positive surface mass density residuals, and are drawn at surface mass density, in terms of critical for lensing of  $\kappa = 0.025, 0.05, 0.1, \dots$ , or, equivalently,  $3.15, 6.3, 12.6, \dots M_{\odot}/\square''$ . The dashed black contours indicate negative surface mass density residuals. Purple contour indicates zero density residual. The reconstruction window has radius  $15.2''$ , the sky scale being  $\simeq 7.5 \text{ kpc}/\text{arcsec}$ ; the full horizontal scale is  $300h_{65}^{-1} \text{ kpc}$ . In each panel the mass maps shown are averages from ensembles of 500; additional smoothing has been applied to the maps using  $\sigma = 0.67''$ . Red dots are QSO images. Blue crosses are galaxies with  $i < 24$ , taken from Fig. 13a of Oguri et al. (2004). *Left*: Prior A. The derived typical galaxy  $M/L \approx 12$ , while the fraction of mass associated with galaxies is  $\sim 9\%$ . *Right*: Prior B. The derived typical galaxy  $M/L \approx 3$ , and the fraction of mass associated with galaxies is  $\sim 2\%$  (see Williams & Saha 2004 for details).

**Method.** The lens is divided into 100-1000 independent mass pixels. Image positions are taken as fixed model (primary) constraints. Because these are greatly outnumbered by the unknowns, secondary constraints are needed. *PixeLens* generates a large number of individual mass maps; we show the ensemble averages, or ‘best estimate’ maps, from the Bayesian point of view.

Secondary Model Constraints, or Priors: (1) No pixel can have a negative mass:  $\kappa \geq 0$ . (2) The lens must be centrally concentrated. *PixeLens* implements this by restricting the direction of the mass density gradient,  $\phi_{\nabla}$  at every pixel’s location. The default value is  $\phi_{\nabla} \leq 45^{\circ}$ , meaning that the density gradient must point within  $\pm 45^{\circ}$  of center. (3) Circularly averaged double logarithmic projected density slope in the image annulus,  $\alpha$  (where  $\rho_{2D} \propto r^{-\alpha}$ ) can be constrained. (4) The influence of a nearby group or cluster can be incorporated as an external shear, whose approximate direction,  $\phi_{\gamma}$ , is a model input. A given input  $\phi_{\gamma}$  allows any shear direction within  $\pm 45^{\circ}$  of  $\phi_{\gamma}$ .

**Results.** We show results using two sets of priors: *Prior A* has  $\phi_{\nabla} \leq 45^{\circ}$ , while *Prior B* has  $\phi_{\nabla} \leq 8^{\circ}$ . For both,  $0.25 \leq \alpha \leq 3$ , and  $\phi_{\gamma} = 10^{\circ} \pm 45^{\circ}$ . We experimented with several other types of priors. The basic results do not change: (1) All recovered mass maps show the Northern and the South-Eastern galaxy groupings; (2) Fraction of cluster mass associated with individual galaxies  $\lesssim 10\%$ ; (3) Typical  $M/L$  per galaxy is  $\lesssim 15$ .