CLUSTER MASS PROFILE FROM LENSING

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We propose a new technique to reconstruct non-parametrically the projected mass distribution of galaxy clusters from their gravitational lens effect on background galaxies. The beauty of our technique, is that it combines information from multiple imaging (strong lensing) and shear (weak lensing) as linear constraints on the projected mass distribution. Moreover, our technique overcomes all the drawbacks of non-linear methods. The method is applied to the first cluster-lens A370 and to the cluster-lens A2218 which is exceptionally rich in multiple images and arc(let)s. The reconstructed maps for both cases revealed unprecedented level of details.

1 Introduction
Gravitational lensing provides us with the necessary information (constraints) needed for probing the matter distribution of cosmic lenses. We present a new technique that combines information from strong and weak lensing in a linear fashion and reconstructs mass maps that follows the cluster light distribution as closely as possible while strictly preserving the lensing constraints. Our technique overcomes many of the drawbacks of previous methods: (a) It’s non-parametric, like Kaiser-Squires and related weak lensing methods but unlike previous strong lensing work, (b) Error estimates are easy, (c) Lensing constraints remains linear in all regimes (strong, weak & intermediate), (d) No mass sheet degeneracy and no end (boundary) effects.

2 Outline of the method
The technique works with a pixellated mass distribution, i.e the mn-th pixel is a square tile with a surface mass density \( \kappa_{mn} \) in units of the critical density. For a source at an unlensed position \( \beta \), the scaled time delay in a direction \( \theta \) is

\[
\tau(\theta) = \frac{1}{2}(\theta - \beta)^2 - \frac{D_{ls}}{D_{s}} \sum_{mn} \kappa_{mn} \psi_{mn}(\theta),
\]

where \( \psi_{mn}(\theta) \) (a known function) is how much the mn-th pixel would contribute to the potential.

\(^a\)Other types of pixels are also viable and produce similar mass maps.
Cluster lensing observations provide us with the following constraints:

(i)– Image positions, say $\theta_1$, implying

$$ \nabla \tau(\theta_1) = 0. $$

(ii)– Shear measurements at some $\theta_1$; say the shear is observed to be at least $k$, and aligned along the $\theta_x'$ direction. This implies

$$ k \left| \frac{\partial^2}{\partial \theta_x'^2} \tau(\theta_1) \right| \leq \left| \frac{\partial^2}{\partial \theta_y'^2} \tau(\theta_1) \right|. $$

Both types provide linear constraints on the unknowns $\beta$ and $\kappa_{mn}$.

By quadratic programming, we can produce the mass maps that e.g., minimize $M/L$ variations while obeying the lensing constraints. By minimizing $M/L$ variations with respect to Monte-Carlo light distributions, we can estimate errors.

3 Abell 370

![Figure 1](image.png)

Figure 1: **Left**: Sky projected mass distribution of Abell 370. Mass enclosed by the dashed rectangle is $2.1 \times 10^{14} h_{50}^{-1} M_{\odot}$. **Right** Fractional uncertainty of the mass map.

Our reconstruction of Abell 370, using only the constraints from multiple images (strong lensing), is shown in Fig. 1. The reconstructed mass map predicted the bimodal nature of the cluster and robustly revealed features not associated with light (for more details see AbdelSalam et al 1997).

Our reconstruction indicates that the radial arc, recently discovered in the HST image, may be five images out of a seven image configuration.
4 Abell 2218

Our mass reconstruction for A2218, using the constraints from combined strong and weak lensing, is shown in Figure 2 (left) and the uncertainties are shown in Figure 3. Our reconstructions of the inner region of Abell 2218 uses both multiple image data (strong lensing) and singly imaged arc(lets) (weak lensing) from HST, plus spectroscopic redshifts from Ebbels et al 1997. As far as we are aware this is the first mass reconstruction using strong and weak lensing simultaneously.

As Miralda-Escudé & Babul (1995) first noted, current X-ray mass models appear to underestimate the mass. Our results reinforce this conclusion: mass estimate from lensing is at least 2.5 times that from X-ray models (Figure 2 (right)). This may indicate the gas is partially supported by turbulence or magnetic fields, the gas is not uniform and isothermal or is not in equilibrium, but rather multiphase or has temperature gradient rising inwards; or the cluster is elongated along the line of sight.

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Figure 3: **Left:** Mass distribution of Abell 2218 plus (left) and minus (right) one standard deviation uncertainty.

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