Cluster Mass Reconstruction Using Gravitational Lensing

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Cluster Formation

Andrey Kravtsov
Gravitational Lensing

\[ \chi^2 = \mu^2 (1) \]

\[ \alpha \chi^2 = \mu^2 (1) \]

\[ \alpha \beta \theta \kappa = \sum \sum c r (2) \]

Strong Lensing

Weak Lensing

\[ \kappa = \frac{\sum}{\sum c r} \]
Observables

Weak Lensing: Ellipticities

Reduced shear: \( g = \gamma/(1 - \kappa) \)

Strong Lensing: Difference of angular positions

\[ \alpha_A - \alpha_B = \theta_A - \theta_B \]
What do we want to measure?

- Mass
- Ellipticity
- Morphology

Why?

Test Predictions of LCDM cosmology?
Compare with the morphologies of gas and light.
Introduction

Elliptical Halos: Substructure

What is the distribution of cluster ellipticity?

How aligned are clusters with neighbors?

How does the distribution and alignment vary with redshift & mass?
Predictions from Simulations

Hopkins et al. 2005

Ho et al. 2006
Morandi et. al. 2009 have measured the line-of-sight ellipticity by joint analysis of X-ray and lensing measurements.
Mass Reconstruction Challenges

HST/ACS image of Abell 2218 (Sánchez et al. 2006)
Reconstruction Technique: Particle Based Lensing

- No empty grid cells.
- Simplicity of uniform gridding
- Flexibility of adaptive gridding
- Noise Covariance matrix has been calculated.
Inverse Techniques

Keep Iterating ...

1. Guess a potential field $\psi$

2. Compute observables $\kappa, \varepsilon = \frac{\gamma}{(1-\kappa)}$

3. $\chi^2$ minimization

$\chi^2_{\text{weak}} = \sum_m \left[ \frac{\varepsilon_m - \frac{\gamma_m}{(1-\kappa_m)}}{\sigma_m^2} \right]^2$

In case of weak lensing, a $\chi^2_{\text{w}}$ like this will fit best to noisy data

Smoothing the ellipticity field before minimization and using the full covariance matrix in the minimization

$$\sum_{mn} \left( \varepsilon_m^i - \frac{\gamma_m^i(\psi_m)}{1-\kappa_m(\psi_m)} \right) \frac{1}{\sigma_{mn}} \left( \varepsilon_n^i - \frac{\gamma_n^i(\psi_n)}{1-\kappa_n(\psi_n)} \right)$$
Preliminary results: Bullet Cluster

From Deb, Goldberg & Ramdass, 2008
Abell 901/902

0.5 degree$^2$ fov
STAGES HST survey
60,000 background images.

60 images per square arc minute
A901b

Mass Map

Error Map
Introduction                     Elliptical Halos                   Particle Based Lensing
Abell 901/902    Abell 1689                  Conclusions                     Future  Work

A902

Mass Map

Error Map
Southwest Group

Mass Map

Error Map

Introduction                     Elliptical Halos                   Particle Based Lensing
Abell 901/902                  Abell 1689                  Conclusions                  Future Work
### Ellipticity Measurements: Dark Matter

<table>
<thead>
<tr>
<th>Peak</th>
<th>Axis Ratio</th>
<th>Position angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>A901b Parametric</td>
<td>$0.437^{+0.1}_{-0.087}$</td>
<td>$90.0^{+2.25}_{-2.25}$</td>
</tr>
<tr>
<td>A901b Non-Parametric</td>
<td>$0.37^{+0.1}_{-0.1}$</td>
<td>$91.4^{+8.2}_{-8.2}$</td>
</tr>
<tr>
<td>SW Group Parametric</td>
<td>$0.42^{+0.18}_{-0.12}$</td>
<td>$180.0^{+7.73}_{-5.15}$</td>
</tr>
<tr>
<td>SW Group Non-Parametric</td>
<td>$0.54^{+0.08}_{-0.09}$</td>
<td>$120.0^{+4.8}_{-4.8}$</td>
</tr>
</tbody>
</table>

Deb et. al 2009
Dark Matter vs Light

<table>
<thead>
<tr>
<th>Peak</th>
<th>Light</th>
<th>Dark Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>A901b</td>
<td>$0.81^{+0.1}_{-0.09}$</td>
<td>$0.37^{+0.1}_{-0.1}$</td>
</tr>
<tr>
<td>SW Group</td>
<td>$0.70^{+0.06}_{-0.05}$</td>
<td>$0.54^{+0.08}_{-0.09}$</td>
</tr>
</tbody>
</table>

Deb et. al 2009
Alignment
X-ray vs Weak Lensing: Radial profile
X-ray vs Weak Lensing: Maps

Introduction  Elliptical Halos  Particle Based Lensing  Abell 901/902  Abell 1689  Conclusions  Future Work
Strong+Weak Lensing

Deb et. al 2010 (in prep)
X-ray+Lensing

Introduction                     Elliptical Halos                   Particle Based Lensing                 Abell 901/902

Abell 1689

Conclusions                     Future Work
Conclusions

The ellipticity for the light distribution is smaller than the ellipticity of the dark matter distribution for A901b and the Southwest Group.

A901a, A901b and A902 have strong alignment whereas the Southwest group is not aligned with the rest of the peaks.

The weak lensing analysis of A1689 shows a spherical distribution whereas inclusion of strong lensing reveals substructure.

Further Reading

Future Work

Multiwavelength shape analysis of galaxy clusters.

Sample of 10 X-ray selected clusters:
- Lensing data: Hakon Dahle
- X-ray data: Chandra archival data
- SZ data: Future plans of writing CARMA proposals with Dr. Morandi.

Clusters are being discovered as we speak with SZ experiments like ACT/SPT. Lensing observations of these clusters will also increase this data set.