Precise measurement of dark matter distribution with strong and weak gravitational lensing

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This talk is based on:

“Combined strong and weak lensing analysis of 28 clusters from Sloan Giant Arcs Survey”


Collaborators:

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Cluster of galaxies

- most massive virialized objects in the universe
- structure mostly determined by the dynamics of dark matter
- can be a good site to test structure formation models

http://www.mpa-garching.mpg.de/galform/millennium/
Expected mass distribution in $\Lambda$CDM

**Cuspy**
so-called NFW profile, slope gets shallower toward the center

**Concentration**
correlated with mass, more massive halos are less concentrated

**Triaxial**
not spherical, highly elongated

http://www.mpa-garching.mpg.de/galform/millennium/
Anomalously high concentration?

• lensing analysis of Abell 1689
  \( c_{\text{vir}} \sim r_{\text{vir}}/r_s \sim 12 \)

• much larger than typical \( c_{\text{vir}}(\sim 4) \), may hard to reconcile with \( \Lambda \text{CDM} \)

• controversial
  \( \rightarrow \) other clusters?
Sloan Giant Arcs Survey (SGAS)

Hennawi et al. (2008), Bayliss et al. (2011)
Gladders et al., in prep.

• based on optical (red-sequence) clusters from the Sloan Digital Sky Survey

• look for strong lenses by visual inspection of SDSS or follow-up images

• >40 clusters with prominent giant arcs discovered, extensive arc spectroscopy w/ Gemini/GMOS
Strong gravitational lensing

- strong deflections of light rays which produce multiple images or highly elongated shapes of galaxies
- provide a robust core mass measurement of clusters (w/ redshift info)
Cluster is much bigger...
Weak gravitational lensing

- coherent distortions of shapes of background galaxies
- measured by averaging many galaxies’ shapes
- can measure cluster mass profiles out to virial radius

(simulation by T. Hamana)
Subaru/Suprime-cam follow-up

- world best telescope for cluster weak lensing!
- gri-band imaging
  \( (g \sim 20\text{min}, \, r \sim 40\text{min}, \, i \sim 30\text{min}) \)
- \(~7\) nights allocated from 2007 to 2011 (PI: M. Oguri)
  [Thank you!]

\[\rightarrow\text{strong+weak lensing analysis for \sim30\text{ clusters}}\]
Example of strong+weak lensing analysis

- Strong and weak lensing results are complementary, leading to robust profile observation
Mass-concentration relation

- mass dependence of $c_{\text{vir}}$ detected
- slope too steep? ($c_{\text{vir}} \propto M_{\text{vir}}^{-0.59\pm0.12}$) (cf. Okabe et al. 2010)
- $c_{\text{vir}}$ consistent w/ theoretical prediction at high mass
- low mass excess probably due to baryon cooling

\[ \Omega_{\text{CDM}} \text{ prediction w/ lensing bias + triaxiality} \]

our sample from literature (Umetsu et al. 2011; Zitrin et al. 2011)
Stacked lensing analysis

- combine weak lensing shear measurements for many clusters
- higher S/N, leading to accurate mean profile measurement
Stacked lensing analysis

25 clusters stacked  \langle z \rangle = 0.469

\langle \theta_E \rangle = 14.4^{+10.6}_{-7.0} \text{[arcsec]}
\langle M_{\text{vir}} \rangle = 4.57^{+0.33}_{-0.31} \times 10^{14} h^{-1} M_\odot
\langle c_{\text{vir}} \rangle = 5.75^{+0.70}_{-0.57}

- high S/N lensing shear profile by stacking 25 clusters
- follow NFW well

\langle \Delta \Sigma_x \rangle \ [10^{15} h M_\odot \text{Mpc}^{-2}]
\langle \Delta \Sigma_x \rangle \ [10^{-2}]
\langle \Delta \Sigma_x \rangle \ [0.2]
\langle \Delta \Sigma_x \rangle \ [-0.2]

r \ [h^{-1} \text{Mpc}]
distance from center

strong lens constraint
Stacked lensing analysis

- best-fit M-c relation from individual analysis of clusters
- $\Lambda$CDM prediction w/ lensing bias + triaxiality
- consistent with individual analysis

$M_{\text{vir}}$ [$10^{14}h^{-1}M_\odot$] [cluster mass]

$\theta_E$ bin
$M_{\text{vir}}$ bin
Umetsu+11b
Shape: 2D stacking analysis

strong lens modeling

rotate $-\theta_{\text{PA}}$

stacked weak lensing analysis

(No assumption on mass-light alignment!)
The result without any alignment of the position angle when stacking. The resulting mass distribution is nearly circular, which supports that the highly elongated distribution in our catalogue is an artifact.

The result when the position angle of each cluster is aligned to rotate the catalogue of the background galaxies by such that the the position angle of the dark halo is aligned to the North-South axis before stacking, by using the position angle obtained in strong lens mass modelling (physical length scale. For each cluster, we adopt the position angle analysis.

The two-dimensional weak lensing shear maps obtained from stacking. The resulting density distribution is indeed quite elliptical, and the contribution of the large scale structure to the error covariance matrix is minor.

We stack the rotated shear catalogue in the physical unit, to rotate the catalogue of the background galaxies by such that the the position angle of the dark halo is aligned to the North-South axis before stacking, by using the position angle obtained in strong lens mass modelling (physical length scale. For each cluster, we adopt the position angle analysis.

As in Section 5.1, we conduct stacking analysis in the 2D shear plane, and the two shear components \( \kappa_x \) and \( \kappa_y \), to obtain the average 2D shear map of our cluster sample. The stacked 2D shear map, as well as the corresponding density contour as simply by introducing the ellipticity in the iso-density contour as.

The projected mass density is clearly elongated along the North-South direction, suggesting the highly elongated mass distribution by directly fitting the 2D shear map with the elliptical NFW model prediction. Here we closely follow the fitting procedure our definition of the ellipticity is

\[
\epsilon = \frac{b - a}{a} = \frac{\theta_{2} - \theta_{1}}{\theta_{1}}
\]

where \( \theta_{1} \) is the major axis and \( \theta_{2} \) is the minor axis lengths of the isodensity contour. The corresponding shear pattern is computed by solving the Poisson equation. We then construct pixelized distortion field by computing mean shear and errors from the shear map

\[
\left( \begin{array}{c}
\kappa_x \\
\kappa_y
\end{array} \right) = \left( \begin{array}{c}
\frac{1}{2} \kappa_x \\
\frac{1}{2} \kappa_y
\end{array} \right)
\]

with the shear measured in strong lens modelling. The resulting stacked density distribution is nearly circular, which supports that the highly elongated distribution in our catalogue is an artifact.

We constrain the ellipticity of the projected 2D mass distribution by directly fitting the 2D shear map with the elliptical NFW model prediction. Here we closely follow the fitting procedure our definition of the ellipticity is

\[
\epsilon = \frac{b - a}{a} = \frac{\theta_{2} - \theta_{1}}{\theta_{1}}
\]

where \( \theta_{1} \) is the major axis and \( \theta_{2} \) is the minor axis lengths of the isodensity contour. The corresponding shear pattern is computed by solving the Poisson equation. We then construct pixelized distortion field by computing mean shear and errors from the shear map

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with the shear measured in strong lens modelling. The resulting stacked density distribution is nearly circular, which supports that the highly elongated distribution in our catalogue is an artifact.

In Figure 12, we show the posterior likelihood distribution of the mean ellipticity \( \langle \epsilon \rangle \) from the 2D stacking analysis

\[
\langle \epsilon \rangle = \frac{1}{n} \sum_{i=1}^{n} \epsilon_i
\]

where \( n \) is the number of clusters. When the position angles are aligned, the resulting density distribution is indeed quite elliptical, and the contribution of the large scale structure to the error covariance matrix is minor.
Constraint on mean ellipticity

\( \Lambda \)CDM prediction (Jing & Suto 2002)

Aligned PA:
\[ e = 0.47 \pm 0.06 \]

Random PA:
\[ e < 0.19 \]

- ellipticity detected at \( 5 \sigma \) level
- mean ellipticity consistent w/ \( \Lambda \)CDM

[see also Oguri, Takada, Okabe & Smith (2010)]
Summary: testing halo profiles

• NFW-like radial density profile ($r^{-1}$ inner, $r^{-3}$ outer)
  observed profile consistent with NFW

• concentration (low, correlated with mass)
  steep mass dependence
  consistent with $\Lambda$CDM at high mass
  larger $c_{\text{vir}}$ at small mass due to baryon cooling

• large non-sphericity (axis ratio $a/c \sim 0.4$)
  excellent agreement with $\Lambda$CDM

$\Lambda$CDM works remarkably well at cluster scale!