Measuring masses using weak gravitational lensing

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Clusters have a complicated history of multiple mergers resulting in complicated geometries with a lot of substructure. This is particularly important at high redshifts.
Gravitational lensing

Inhomogeneities in the matter distribution deflect light rays and cause coherent distortions in the shapes of distant galaxies.
Weak gravitational lensing

A measurement of the ellipticity of a *single* galaxy provides an unbiased but noisy measurement of the gravitational lensing shear.
What do we measure?

Underlying assumption: *the source position angles are uncorrelated in the absence of lensing.*

- Measure the galaxy shapes from the images
- Correct for observational distortions
- Select a sample of background galaxies

Lensing signal

The conversion of the lensing signal into a mass requires knowledge of the source redshift distribution
PSF correction

It is relatively easy to create simulated data to test the measurement techniques.

The Shear TEsting Programme is an international collaboration to provide a means to benchmark the various methods. This has evolved into a challenge to involve computer scientists: GREAT’08 & GREAT’10.

We can currently reach an accuracy of 1-2% in the shear measurement.
A handful of clusters were studied in the ’90s using cameras with relatively small fields of view and little knowledge of the source redshift distribution.
Modern cluster lensing

Improvements since the early days:

- measure signal out to larger radii
- better knowledge of the source redshift distribution
- better corrections for systematic effects

As the sample sizes increase, the lensing analysis needs to become more advanced: deal with contamination by cluster galaxies, centroid errors, contributions from local and distant large scale structure, etc.
Limitations of weak lensing

• Weak lensing yields the projected mass distribution.
• The signal depends on all matter along the line of sight.
• We require good knowledge of the source redshifts.
• Need to account for contamination by cluster members.
• What to pick as the cluster centre?

The last point is particularly problematic if we fit a simple parametric model and is made worse if there is substructure!

Use aperture masses (1-d masses):

- This can minimize the model dependence
- This reduces the sensitivity to the centroid
- Also reduces contamination by cluster members
- Small bias (Becker & Kravtsov 2011)
Effects of ‘cosmic noise’

Hoekstra (2003)

Uncorrelated large scale structure is an additional source of noise

- Limits the accuracy with which masses can be determined
- Lowers the true significance of peaks in a mass reconstruction
Effects of ‘cosmic noise’

Cosmic noise is very important for studies of the mass profile.
Applications

- Map the matter distribution
- Calibrate scaling relations
- Study cluster physics
We can ‘see’ dark matter

In the absence of noise we would be able to map the matter distribution in the universe (even “dark” clusters). We need high source densities: best using HST data.
CCDs in space degrade due to radiation damage. Charge Transfer Inefficiency (CTI) introduces spurious signal.

Jee et al. (2012)
A recent analysis using WFPC2 data is in excellent agreement with our puzzling ground based results...

\[ M/L_B = 588 \pm 56 \]
We have two options to study cluster samples:

**Masses for individual clusters:**
- study scatter
- expensive
- only massive clusters

**Masses for ensembles of clusters:**
- cheap
- large range in mass (and redshift)
- but how to bin?
- what about intrinsic scatter?
Lensing by individual clusters

Abell 223
Mahdavi et al. (in prep): gas is not always in hydrostatic equilibrium.
Evolution of M-T relation

Normalization 20-30% lower at $z \sim 1$

Jee et al. (2011)
More CCCP results

“real” SZ (Bonamente et al.)

“X-ray” SZ (CCCP)

- $S < 100 \text{ keV cm}^2$
- $S > 100 \text{ keV cm}^2$

$E_{z}^{-2/3}D_{\text{ang}}^{2} Y \left[ \text{Mpc}^2 \right]$

$E(z)^{2/5}M_{\text{WL}}(r_{\text{X-ray}}) \left[ h^{-1}M_{\odot} \right]$

$Y_{X} \left[ M_{\odot} \text{keV} \right]$
Planck & SPT observations

Samples with WL and SZ measurements are increasing rapidly.

CCCP

SPT

High et al. (2012)
Stacking clusters

If the masses are too low, one can still learn about the cluster properties by stacking the signal of many systems. This is for instance done for galaxy groups (Hoekstra et al. 2001; Parker et al. 2006). See also talk by Giodini

Similarly, although the SDSS imaging is not deep enough to study the masses of individual clusters, the signals of similar systems can be combined.

For instance this allows studies of the cluster mass profile out to large radii
Cluster density profiles

Johnston et al. (2007)
RCS2 - 28,000 CLUSTERS

van Uitert et al. (in prep)
RCS2 - 28,000 CLUSTERS
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We can start to study the evolution of the mass-richness relation

van Uitert et al. (in prep)
KiDS + VIKING: (1500 deg$^2$,ugriZYJHK )
- has started fall 2011
- goal is completion in ~3 years

>2019: Euclid will improve S/N per cluster by a factor ~2-3
One more reason to care

Weak lensing by large scale structure (cosmic shear) is one of the most powerful probes of dark energy.

But... the correct interpretation of the signal from future projects, such as Euclid, requires an improved understanding of the baryon feedback processes in groups and clusters of galaxies.
van Daalen et al. (2011): feedback can modify the matter power spectrum significantly
We cannot ignore (g)astrophysics

Semboloni et al. (2012)

Ignoring feedback

Accounting for feedback
Halo model with baryons

Current simple model:
- galaxies are point masses with a luminosity
- gas follows beta-model with some fraction removed
Despite its simplicity the model already reduces the biases in cosmological parameters to a level comparable to the statistical error.

Constraints from SZ and X-ray observations should provide important additional constraints, reducing biases even further.
Conclusions

Weak lensing studies of clusters, groups and galaxies provide important information to link observations to simulations, which in turn leads to a better understanding of baryon physics.

Sample sizes are increasing rapidly (KiDS, DES, Euclid). Therefore it is important that the analyses become more sophisticated.