Mapping the Dark Matter: Mass Selected Galaxy Clusters from Weak Lensing

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Outline

- Galaxy clusters from weak lensing
- Dark clusters?
- Cluster Tomography
- N-body simulations
- Optimal filtering
- Constraining dark energy

Gravitational Lensing

Galaxy Cluster Abell 2218
HST • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08
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Weak Lensing by Large Scale Structure

First Mass-Selected Cluster
(Wittman et al. 2001)

- First cluster discovered through its lensing effect rather than radiation!
- $\sigma_{\text{vel}} = 615 \text{ km s}^{-1}$
- $z_{\text{spec}} = 0.28$
- Deep Lens Survey (DLS)
  - 28 deg$^2$
  - could find ~ 200 clusters
- LSST
  - 30,000 deg$^2$
  - up to 300,000 clusters
Mass-Selected Cluster Samples

How can we find clusters of galaxies?
- Optical
- X-ray
- Sunyaev-Zeldovich effect
- Weak lensing survey

Biased?

The first Mass-Selected cluster sample WILL:
- Determine biases in other cluster samples
  - richness and morphology?
  - relaxed or merging?
- Test the “fair sample” hypothesis used to determine $\Omega_m$. Is there a class of high M/L clusters?
- Number counts. Cosmological parameters with little assumption about baryons in clusters

CONSTRAIN DARK ENERGY

Is there a population of DARK CLUSTERS?

The Case For Dark Clusters

(circa 2002)
**Exhibit A: WL 1017.3+5931**
(Dahle et al. 2002)

- Primary peak is a bright X-ray cluster Abell 1959 at $z = 0.29$
- No significant concentration of early type galaxies at position of secondary peak, $M/L > 500$.
- Secondary peak is at least a factor of two X-ray underluminous if at $z = 0.29$

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**Exhibit B: Q2345+007 -- Binary QSO or Dark Lens?**
(Steidel & Sargent 1991; Green et al. 2002; Tyson et al in prep 2003)

- Most prominent wide-separation quasar pair (WSQP) with $\Delta \theta = 7.7^\prime$
- The masses required for such large image splittings are $M = 10^{14} M_\odot$
- Deep Chandra observations indicate that any cluster would have a baryon fraction a factor of $\sim 3$ lower than known clusters
- Four other WSQP’s with similar spectra, identical redshifts, and no lens galaxy exist.

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**Exhibit C: Abell 781 vs DLS #??**

- Mass map
- Chandra
- Abell 781
- Mystery Object

- Mass map
- R band images

**Cluster Tomography**

- Distant Source Galaxies
- Galaxy Cluster @ z = 0.5
- Foreground Source
- Lens Strength
  \[ \frac{\sum_{\text{crit}} \alpha \left| \frac{D_{\text{lens}}}{D_{\text{source}}} \right|}{\sum_{\text{crit}}} \]
- Source Redshift Distribution
  \[ P(z) \]
- Lens Strength
  \[ z_{\text{lens}} = 0.5 \]

The blue galaxy is sheared more than the red galaxy.
The green galaxy is not sheared.
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**Cluster Tomography**
(Wittman et al. 2001, 2002)

- Assume a mass profile and fit for shear as a function of source photometric redshift
- $z_{\text{spectra}} = 0.28$
- photo z’s + tomography

$z_{\text{lensing}} = 0.30$

How reliable is this technique?

**Weak Lensing Simulations**

- Tile the light cone with N-body simulation cubes (White & Hu 1999)

- Project the matter distribution to determine the shear field at the observer

- Place mock source galaxies at random positions, consistent with observed number densities and intrinsic ellipticities

- Shear the mock galaxies with the shear field
Weak Lensing Simulations

- Smooth the shear field with an “optimal filter” and search for peaks.
- Apply a group finder to find collapsed halos. Detected clusters are traced back to simulations cubes for cluster statistics.

Advantages of Simulations

- Properly simulate alignments and projections, which can be severe.
- The selection function can be simulated for any cosmology, foregoing the need to acquire a “complete” sample.
- Mock observations allow us to Monte-Carlo simulate parameter estimates, for realistic error forecasts.
- Fast Particle Mesh (PM) algorithm:
  - simulate large areas of sky to accurately represent the statistics of rare events (every cluster is unique)
  - allows rapid exploration of parameter space
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Cluster Tomography

- $z_{\text{real}} = 0.63$
- $z_{\text{lensing}} = 0.67$
- $M = 1.0 \times 10^{15} M_{\odot}$

Wrong!

Projections & Alignments

- $z = 0.33$
- $26'$
- $57 \text{ Mpc}$
- (10 Mpc slab)

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**Optimal Filtering**

- “Noise” in weak lensing searches for clusters requires that shear maps be smoothed
  - white noise from finite sampling and intrinsic ellipticities
  - confusion from large scale structure
  - projection effects
- For white noise a “matched filter” will optimally extract a signal of known shape
- Galaxy clusters are identified as the peaks in smoothed maps that lie above a threshold $\nu$
- For any given threshold $\nu$ define the efficiency as the ratio
  $$\text{efficiency} = \frac{n_{\text{clusters}} (> \nu)}{n_{\text{peaks}} (> \nu)}$$

**Adaptive Matched Filter**

- In the absence of source redshifts, the observable is the mean shear averaged over the source redshift distribution
  $$\bar{\gamma} = \int P(z) \gamma(z) \, dz$$
- Two filters have been widely used on this quantity
  - Gaussian
  - Aperture Mass $M_{ap}(\theta)$
- If photometric redshifts are available for some sources, tomography and matched filtering can be combined.
- *Adaptive Matched Filtering* uses redshift information to optimally weight source galaxies, producing a likelihood and tomographic redshift for each line of sight
**Adaptive Matched Filter**

- The maximum intrinsic efficiency of weak lensing cluster surveys is ~ 80%.
- Dark clusters cannot be distinguished from the projections, but statistical conclusions can be made.
- For the most significant detections, the dispersion in tomographic redshifts is still $\sigma_z \sim 0.2$
- Photo z’s increase the number of clusters detected by 10-20%.

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**Adaptive Matched Filter**

The Adaptive Matched Filter detects more clusters at high redshift and low mass.
**Cluster Counting Basics**

- **Goal:** Determine cosmological parameters by comparing the observed distribution of clusters to predictions from theory/N-body simulations
- **However** cluster mass is not an observable. Instead we measure:
  - SZ decrement
  - X-rays ($L_X$ or $T_X$)
  - Richness
  - Galaxy $\sigma_v$
  - Shear $\gamma$
- **To interpret the observations we must know**
  - $M(\text{observables},z)$
  - Completeness(observables,$z$)

**Cluster Counting Caveats**

- Usually one writes
  \[
  \frac{dN}{d\Omega dz}(w) = \frac{dV}{d\Omega dz} \int_{M_{\text{limit}}(z)}^{\infty} C(M,z) \frac{dn}{dM} (M,z | w) dM
  \]

- **The mass function is steep and exponentially sensitive to errors in $M_{\text{limit}}(z)$ and uncertainty in $M(\text{observables},z)$.** These errors mimic cosmological parameter changes!
- **Until these relationships (and their scatter) can be empirically calibrated, this test relies on uncertain assumptions about baryons in clusters**
- **Solutions:** Either determine $M_{\text{limit}}(z)$ from your cluster survey, or devise a test that is insensitive to the limiting mass.
**CMB Degeneracy**

Quintessence parameter ‘w’

\[ \rho_{DE} = w \rho_{DE} \]

\[ w = 0 \rightarrow \text{matter} \]
\[ w = -1 \rightarrow \Lambda, \text{cosm const} \]
\[ w = 1/3 \rightarrow \text{radiation} \]

\[ \rho_{DE} \propto (1+z)^{(1+w)} \]

Parameter combinations that leave the angular diameter distance to the last scattering surface and the physics of acoustic oscillations unchanged produce identical CMB power spectra.

**Cosmic Shear Degeneracy**

Cosmic Shear Power Spectrum

LCM: [\Omega_m = 0.29, \Lambda = 0.71, h = 0.68, \sigma_8 = 0.84, w = -1]

QCDM: [\Omega_m = 0.40, \Omega_\Lambda = 0.6, h = 0.58, \sigma_8 = 0.73, w = -2/3]

Simulated

Analytical

Linear theory power spectra

Non-linear power spectra

Intrinsic ellipticity shot noise

all sources @ $z_s = 1.0$
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**Breaking the Degeneracy**

![Graph showing growth factor, volume element, and lensing kernel for LCDM and QCDM models.](image)

**LCDM:** $\Omega_\gamma = 0.29$  $\Lambda = 0.71$

$h = 0.68$  $\sigma_8 = 0.84$  $w = -1$

**QCDM:** $\Omega_\gamma = 0.40$  $\Omega_\Lambda = 0.6$

$h = 0.58$  $\sigma_8 = 0.73$  $w = -2/3$

**Breaking the Degeneracy**

![Graph showing comoving and angular number densities of clusters for LCDM and QCDM models.](image)

**LCDM:** $\Omega_\gamma = 0.29$  $\Lambda = 0.71$

$h = 0.68$  $\sigma_8 = 0.84$  $w = -1$

**QCDM:** $\Omega_\gamma = 0.40$  $\Omega_{\Omega} = 0.6$

$h = 0.58$  $\sigma_8 = 0.73$  $w = -2/3$
QCDM or LCDM?

- Redshift distributions differ at a high statistical significance
- The lensing efficiency is broader for LCDM than for QCDM, and thus probes a broader range of \( z \) and \( M \)
- Unlike other cluster counting surveys, this test is ROBUST against uncertainties in mass limit.

Conclusions

- Fast numerical simulations of weak lensing are a valuable tool to accurately predict cluster statistics over a large region of parameter space
- Using photo \( z \)'s with an Adaptive Matched Filter detects up to 10-20% more clusters and recovers more clusters at high redshift and low mass.
- Even for the most significant detections, the dispersion in tomographic redshifts is still \( \sigma_z = 0.2 \).
- Weak lensing cluster surveys are plagued by projections --- the maximum intrinsic efficiency is ~ 80%.
- Only statistical statements about a population of dark clusters can be made from weak lensing
- The normalized redshift distribution of mass selected clusters is a powerful probe of dark energy and is insensitive to uncertainties in the mass limit.