Probing the Dark Universe with Weak Gravitational Lensing

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With David Bacon, Meghan Grey, Michael Brown, Tom Kitching, Chris Wolf, Klaus Meisenheimer, Bhuvnesh Jain
The “Standard Model” of Cosmology

- **WMAP, SNIa, 2dFGRS, Sloan Digital Sky Survey:**
  - 70% Dark Energy
  - 25% Dark Matter
  - 5% Baryonic Matter
  - Spatially flat

- **Four outstanding problems:**
  - Dark Matter
  - Dark Energy
  - Inflation
  - Galaxy formation
Gravitational Lensing

• Hubble Space Telescope deep field of a galaxy cluster – the large gravitational lens, Abell 2218.
Gravitational Lensing

- A simple scattering experiment:

\[ ds^2 = -(1 + 2\Phi)dt^2 + a^2(t)(1 - 2\Phi)dr_idr^i \]
Gravitational Lens Distortions

- Galaxy ellipticity, $e$:
- Lensing effect:
  \[ e' = e + 2\gamma \]
- On average $\langle e \rangle = 0$.
- So $\langle e' \rangle = 2\gamma$.
- Shear matrix:
  \[ \gamma = \gamma_1 + \gamma_2 \]
Weak Lensing

• An observable is the shear (2-d tidal) matrix:

\[
\gamma_{ij} = \left( \partial_i \partial_j - \frac{1}{2} \delta_{ij} \partial^2 \right) \phi = \begin{pmatrix} \gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{pmatrix}
\]

(Take derivatives on sky.)

• The 2-d lensing scalar potential, \( \phi \), is a projected Newtonian potential, \( \Phi \):

\[
\phi(r, \theta) = 2 \int_0^r dr' \left( \frac{r - r'}{rr'} \right) \Phi(r')
\]
Mapping the Dark Matter

- From shear to projected density (Kaiser & Squires, 1993):

\[ \phi = 2 \partial^{-4}_{ij} \partial_i \partial_j \gamma_{ij} \]

Surface potential

\[ \kappa = \frac{1}{2} \partial^2 \phi \]

Surface density

\[ = \frac{\Sigma}{\Sigma_c} \]
Supercluster Abell 901/2 in COMBO-17 Survey

- $z=0.16$
- $R=24.5$

Mass and light in Supercluster A901/2

Dark Matter contours, $\kappa$.

Elliptical galaxy light shading.

Error: $\Delta \kappa = 0.02$ (1–contour)

Mapping the Dark Matter in 3-D

- The lens potential, $\phi$, is a radial integral over the 3-D Newtonian potential, $\Phi$:

$$\phi(r, \theta) = 2 \int_0^r dr' \left( \frac{r - r'}{rr'} \right) \Phi(r')$$
Mapping the Dark Matter in 3-D

• With source distances this can be exactly solved to recover the 3-D Newtonian potential: (Taylor 2001)

\[ \Phi(r) = \frac{1}{2} \partial_r r^2 \partial_r \phi(r, \theta) \]
Is 3-D dark matter mapping practical?

- Shot-noise for 3-D dark matter potential map:
  \[ \Delta \Phi = 10^{-7} \left( \frac{n_2}{20/\text{sq arcmin}} \right)^{-1/2} \left( \frac{\Delta z}{0.05} \right)^{-5/2} \left( \frac{z}{0.1} \right) \approx \Phi_{\text{cluster}} < \Phi_{\text{LSS}} \]

- So Wiener filter in redshift:
  \[ \Phi'(z_i) = \left[ S(S+N)^{-1} \right]_{ij} \Phi(z_j) \]
  \[ S_{ij} = \left\langle \Phi(z_i) \Phi(z_j) \right\rangle = S \delta^K_{ij} \]

- Can now resolve clusters.
- 3-D lensing quality data already exists...COMBO-17 has 17 band photometric redshifts with \( \Delta z = 0.01 \).
The 3-D dark matter potential field

(2-σ threshold)

The 3-D dark matter potential and galaxy number density fields

- Potential Field:

- Galaxy number density:

### A901/2 + CB1 Cluster parameters

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Redshift</th>
<th>M (&lt;0.5Mpc)</th>
<th>L(&lt;0.5Mpc)</th>
<th>M/L</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>(10^{13}M_{\odot})</td>
<td>(10^{11}L_{\odot})</td>
<td>(M_{\odot}/L_{\odot})</td>
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<tr>
<td>A901a</td>
<td>0.16</td>
<td>10.8+-2</td>
<td>24.7</td>
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<tr>
<td>A901b</td>
<td>0.16</td>
<td>8.4+-2</td>
<td>13.6</td>
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<tr>
<td>A902</td>
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<td>5.1+-3</td>
<td>19.5</td>
<td>26.2</td>
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<tr>
<td>CB1</td>
<td>0.48</td>
<td>12.0+-6</td>
<td>13.0</td>
<td>92.3</td>
</tr>
</tbody>
</table>

- Estimate projection-free masses of all objects.
- Erratic mass-to-light ratio – non-equilibrium system.
- Modelling with analytic and numerical methods.

Cosmic Shear

- Lensing by the large-scale dark matter distribution.
- First detected by 4 groups in 2000.
Four random fields in COMBO-17 survey

2-D Dark Matter Maps:

- Area = 1 sq deg.
- Depth: $z = 0.8$.
- Scale: 10 Mpc/h.
Cosmic Shear Power Spectrum

- Maximum Likelihood Analysis of Cosmic Shear.
  Measured over 4 random COMBO-17 fields.

\[ z_m = 0.85 \pm 0.05 \]
from photometric redshifts

Shear Amplitude

\[ \frac{C_1}{\sigma^2} \]

Results from Cosmic Shear

• Combine with 2dF Galaxy Redshift Survey & pre-WMAP CMB

\[ \sigma_8 = 0.73 \pm 0.05 \]
\[ \Omega_m = 0.27 \pm 0.02 \]

\[ \sigma_8(\Omega_m/0.3)^{0.49} = 0.71 \pm 0.09 \]

(h=0.72, \( \tau = 0.1 \))

Shear probes the density field at different redshifts:

\[
C_l^{\gamma\gamma}(z, z') = \frac{9}{4} H_0^4 \Omega_m^2 \int_0^{r_H} dr \, P_m(k = l / r(z), z) W^L[r(z)] W^L[r(z')]
\]

Matter power spectrum

\[
P_m(k, z) = \left\langle |\delta(k, z)|^2 \right\rangle
\]
The Growth of Dark Matter Clustering

- Evolution of the matter power spectrum:

\[ P_m(k, z) = \langle |\delta(k, z)|^2 \rangle = Ak^\alpha e^{-z/z_0} \]

\[ \chi^2 - \text{fit to data.} \]

First detection of evolution of Dark matter clustering. A fundamental prediction of Cosmology.

(Bacon & Taylor, et al 2004, MN)
Geometric test of Dark Energy

(Bhuvnesh Jain & AT, 2003, Phys Rev Lett, 91,1302)

- Depends only on $\Omega_v$, $w = p/\rho$ (and $\Omega_m + \Omega_K$).

$$R(\Omega_v, w) = \frac{\gamma(z_1, z_L)}{\gamma(z_2, z_L)} = \frac{r(z_2)[r(z_1) - r(z_L)]}{r(z_1)[r(z_2) - r(z_L)]}.$$
Geometric test of Dark Energy

- Estimate parameters by minimising $\chi^2$-fit over all source configurations.

$$\chi^2 = \sum_{ijmn} \left( R(z_i, z_j | \Omega_L, w) - \frac{\gamma_i}{\gamma_j} \right) \text{Cov}(R, R)^{-1} \left( R(z_m, z_n | \Omega_L, w) - \frac{\gamma_m}{\gamma_n} \right)$$
Geometric test of Dark Energy
(with Tom Kitching and David Bacon)

- Geometric test applied to A901/2 clusters.
- $\Delta w \sim 0.8$ from 3 clusters.
- Uncertainty scales as:

$$\frac{\Delta w}{w} \propto \frac{1}{M} \frac{\sqrt{\sigma_c^2 / N_i + C^{\gamma \gamma}}}{N_{\text{bin}} \sqrt{N_{\text{cl}}}}$$

- $\sim 1\%$ for darkCAM on VISTA.
Measuring the evolution of Dark Energy

- Measure $\Omega_v$ and $w(a)=w_0+w_a(1-a)$.
- Estimate error for SNAP ($z_m=1.5$).
- 10% of sky: $\Delta w=\sim1\%$, $\Delta w_a=\sim10\%$.

Jain & Taylor, PhysRevLett, 2003
darkCAM on VISTA

- Comparison of lensing telescopes grasp (area x fov) and timescales:

  - Proposal to PPARC to start in 2009.
  - w to ~1% accuracy.
  - 3-D dark matter map of sky.

VISTA (Visible & Infrared Survey Telescope for Astronomy)

- darkCAM
Summary

• With 3-D lensing (shear + redshifts) we can now measure the 3-D Dark Matter distribution.

• Detect the growth of Dark Matter clustering.

• And measure the equation of state of dark energy.

• Can measure dark energy properties in near future with darkCAM on VISTA.