Weak Lensing: a Probe of Dark Matter and Dark Energy

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Outstanding questions:

- initial conditions (inflation?)
- nature of the dark matter
- nature of the dark energy
Cosmic Structure Formation

Ingredients:
- initial conditions
- CDM particles
- gravity

→ The statistics and evolution of the density fluctuations depend on cosmology
Weak Gravitational Lensing

Distortion Matrix:

\[ \Psi_{ij} = \frac{\partial \delta \theta_i}{\partial \theta_j} = \int dz \, g(z) \frac{\partial^2 \Phi}{\partial \theta_i \partial \theta_j} \]

→ Direct measure of the distribution of mass in the universe, as opposed to the distribution of light, as in other methods (e.g. Galaxy surveys)
Weak Lensing Shear Measurement

lensed background galaxies

mass and shear distribution
Scientific Promise of Weak Lensing

From the *statistics of the shear field*, weak lensing provides:

- Mapping of the distribution of Dark Matter on various scales
- Measurement of the evolution of structures
- Measurement of cosmological parameters, breaking degeneracies present in other methods (SNe, CMB)
- Explore models beyond the standard cosmological model (ΛCDM)

Jain, Seljak & White 1997, 25’x25’, SCDM
Cosmic Shear Surveys

WHT survey:
16’x8’
R<25.5
20 gals/amin²

Systematics:
Anisotropic
PSF
Cosmic Shear Measurements

Shear variance in circular cells:

\[ \sigma^2_\gamma(\theta) = \langle \gamma^2 \rangle \]

Bacon, Refregier & Ellis 2000*
Bacon, Massey, Refregier, Ellis 2001
Kaiser et al. 2000*
Maoli et al. 2000*
Rhodes, Refregier & Groth 2001*
Refregier, Rhodes & Groth 2002
van Waerbeke et al. 2000*
van Waerbeke et al. 2001
Wittman et al. 2000*
Hammerle et al. 2001*
Hoekstra et al. 2002 *
Brown et al. 2003
Hamana et al. 2003 *  
* not shown
Jarvis et al. 2003
Casertano et al. 2003*
Rhodes et al. 2004
Cosmological Constraints

Shear correlation functions

Massey, Refregier, Bacon & Ellis 2004

\[
\frac{\sigma_8}{\frac{\Omega_m}{0.3}}^{0.51} = 1.09 \pm 0.12
\]
Normalisation of the Power Spectrum

Moderate disagreement among cosmic shear measurements (careful with marginalisation)

This could be due to residual systematics (shear calibration?)

Agreement on average with CMB constraints

Moderate inconsistency with cluster abundance (systematics or new physics?)
Cosmic Shear Field is Non-Gaussian
Skewness


Variance: \( \langle \kappa^2 \rangle \)

Skewness:

\[ S_3 = \frac{\langle \kappa^3 \rangle}{\langle \kappa^2 \rangle^2} \]

→ Skewness depends only weakly on \( \sigma_8 \) and \( h \)
→ break degeneracies

→ Pen et al. find \( \Omega_m < 0.5 \) (90% CL)
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</table>
Dark Energy and Weak Lensing

Dark Energy equation of state:

\[ w = \frac{p}{\rho} \quad (w = -1 \text{ for } \Lambda) \]

modifies:

- angular-diameter distance
- growth rate of structure
- power spectrum on large scales

(Ma, Caldwell, Bode & Wang 1999)

→ \( w \) can be measured from the lensing power spectrum

→ But, there are degeneracies between \( w, \Omega_M, \sigma_8 \) and \( \Gamma \)

Prospects for SNAP

SNAP wide survey

→ SNAP will measure the evolution of the lensing power spectrum and set tight constraints on dark energy
Conclusions

• **Weak Lensing** has emerged as a unique method to map the large scale structure of the Universe
• **Weak Lensing** is sensitive to both dark matter and dark energy
• **Future surveys and instruments** will afford excellent sensitivity and tight constraints on cosmological parameters
• Challenge of **systematics** requires precise understanding of the instrument → similar to a physics experiment
3D Lensing: Statistical

COMBO17: Bacon, Taylor et al. 2004

Growth factor at $k=14\text{Mpc}^{-1}$

Improvements on cosmological constraints

Tomography & cross-correlation cosmography:
Mass-Selected Clusters

Miyazaki et al. 2002
2.1 deg\(^2\) survey with Subaru

- complex relation between mass and light
- bright cluster counts in agreement with CDM models
- discovery of new clusters
Cosmic Structure Formation

Ingredients:
Initial conditions
CDM particles
Gravity

CDM Simulation
Virgo Consortium
Z=50 to 0
Measuring the Shear

Quadrupole moments:

\[ Q_{ij} = \int d^2x \, x_i x_j \, w(\vec{x}) I(\vec{x}) \]

Ellipticity:

\[ \varepsilon_1 = \frac{Q_{11} - Q_{22}}{Q_{11} + Q_{22}}, \quad \varepsilon_2 = \frac{2Q_{12}}{Q_{11} + Q_{22}} \]

Shear:

\[ \Psi_{ij} = \begin{pmatrix} 1 - \kappa - \gamma_1 & \gamma_2 \\ \gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix} \]

Relation:

\[ \langle \varepsilon_i \rangle = P^\gamma \gamma_i \]
Correction Method

KSB Method: (Kaiser, Squires & Broadhurst 1995)

PSF Anisotropy:

\[ \epsilon_g = \epsilon'_g - \frac{P^{sm}}{P^{* sm}} \epsilon_* \]

PSF Smear & Shear Calibration:

\[ \gamma = (P^\gamma)^{-1} \epsilon_g \]

Systematic Effects: PSF Anisotropy

Dark Matter Mapping:
Ground

Wiener filter

Starck, Pires & Refregier 2004

Wavelets
Dark Matter Mapping: Space

Starck, Pires & Refregier 2004
E: Lensing

E/B Decomposition

B: systematics
Cluster Search with Weak Lensing

Cf. Hamana et al. 2003

Space-based surveys: more sensitive for cluster search, easier to compare to other probes (X-rays, SZ, optical)
Advantages of Space

- Space: small and stable PSF
- Larger number of resolved galaxies
- Reduced systematics

Ground based PSF

- HST galaxy
- HST galaxy, sheared
- Some galaxy, viewed from ground
- Some galaxy, sheared, viewed from ground

Space: small and stable PSF
- Larger number of resolved galaxies
- Reduced systematics
Prospect for SNAP

\( z_S > 1.0 \)
\( z_S < 1.0 \)

SNAP wide (300 deg\(^2\))
Rhodes et al. 2003, Massey et al. 2003, Refregier et al. 2003

→ SNAP will measure the **evolution of the lensing power spectrum** and **skewness** and is sensitive to the **non-linear evolution of structures**
Constraints on Dark Energy

SNAP wide (300 deg$^2$)

→ Tomography improves constraints on $w$ by a factor of 2
→ Cosmic shear constraints complementary to those from SNe
3D Lensing: Mapping

Luminosity

$z = 0.17$

A901a
A901b
A902

$z = 0.47$

Gravitational potential

$z = 0.17$

$z = 0.47$

COMBO17: Taylor, Bacon et al. 2004