Challenges in Cosmic Shear

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Cosmology

Credit: NASA
Gravity
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.

Massey et al. review: Refregier 2003
Weak Lensing Shear Measurement

lensed background galaxies

mass and shear distribution
Typical shear of a few %
Cosmic Shear Measurements

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*
vvan Waerbeke et al. 2001
Wittman et al. 2000*
Hammerle et al. 2001*
Hoekstra et al. 2002 *
Brown et al. 2003
Hamana et al. 2003 *
Jarvis et al. 2003
Casertano et al. 2003* 
Rhodes et al 2004
Massey et al. 2004*
Sembolini et al 2005*
Hoekstra et al 2005*
Benjamin et al. 2006*
Fu et al. 2006*
Schrabback et al. 2009*
* not shown
COSMOS Dark Matter Map

COSMOS HST
ACS survey
2 deg²
Massey et al.
2006, Nature
Shear correlation functions

\[ C_{ij}(\theta^{ab}) = \langle \gamma_i^a \gamma_j^b \rangle \]

\[ \sigma_8(\Omega_m/0.3)^{0.51} = 0.79 \pm 0.09 \]
Dark Energy Constraints

Dark Energy parameters:
- Energy density: $\Omega_\Lambda$ in unit of critical density
- Equation of state $w=p/\rho$: $w=-1$ for all $z$ for a cosmological constant $\Lambda$

Constraints:
- Current constraints: 10% on constant $w$
- For definite answers on DE: need to reach a precision of 1% on (varying) $w$ and 10% on $w_a=\frac{dw}{da}$

Astier et al. 2005

Schrabback et al. 2009
# Wide-Field Instruments

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Challenges for Cosmic Shear

• Measurement
  ‣ Photometric redshifts
  ‣ Shape measurement

• Interpretation
  ‣ Astrophysical systematics
  ‣ Non-gaussian field statistics

• Implementation
  ‣ Large Data Volume
  ‣ Quality Control
Shear Measurement Problem

GREAT08 handbook, Bridle et al 08

The Forward Process.

**Galaxies:** Intrinsic galaxy shapes to measured image:

- Intrinsic galaxy (shape unknown)
- Gravitational lensing causes a \textit{shear (g)}
- Atmosphere and telescope cause a convolution
- Detectors measure a pixelated image
- Image also contains noise

**Stars:** Point sources to star images:

- Intrinsic star (point source)
- Atmosphere and telescope cause a convolution
- Detectors measure a pixelated image
- Image also contains noise
where it is assumed that the residual systematics is unknown and future surveys. Our conclusions are summarized in Section 5.

For each type, we consider several possibilities for no redshift evolution; (ii) additive with redshift evolution and (iii) multiplicative. This paper is organized as follows. In Section 2, we describe the formalism that we use to quantify systematic biases. In Section 3, we apply our formalism to cosmic shear surveys by exploring the effect of the systematics in the design of their scale dependence: (i) log-linear systematics; (ii) systematics shape systematics and by studying the joint impact of systematic power spectra are considered, such as in weak lensing tomography, see that the systematic errors can induce a bias that moves the central value rather than the statistical error alone. An interesting criterion is to define a tolerance on the equation of state parameter which needs to be minimized when optimizing future surveys. Our conclusions are summarized in Section 5.

The red error ellipse includes the systematics bias discussed in the parameters, the summation con-

\[ \text{cov} [\hat{p}_i, \hat{p}_j] = (F^{-1})_{ij} \]

\[ F_{ij} = \sum_{\ell} \Delta C_{\ell}^{-2} \frac{dC_{\ell}^{\text{lens}}}{dp_i} \frac{dC_{\ell}^{\text{lens}}}{dp_j}. \]

shape noise per galaxy: \( \delta \gamma \sim 10^{-1} \)

shear signal: \( \delta \gamma \sim 10^{-2} \)

requirement : \( \delta \gamma \sim 3 \times 10^{-4} \) for \( \sigma_{\text{sys}} = 10^{-7} \)

\[ b[\hat{p}_i] = \langle \hat{p}_i \rangle - \langle p_{i}^{\text{true}} \rangle = (F^{-1})_{ij} B_j \]

\[ B_j = \sum_{\ell} \Delta C_{\ell}^{-2} C_{\ell}^{\text{sys}} \frac{dC_{\ell}^{\text{lens}}}{dp_j}. \]

\[ \sigma_{\text{sys}}^2 = \frac{1}{2\pi} \int |C_{\ell}^{\text{sys}}| \ell (\ell + 1) \, d \ln \ell. \]


Paulin-Henriksson et al. 2008
Shear Measurement Methods

- Moment based methods: Kaiser et al 95, Rhodes et al. 99, Bernstein 10
- Shape fitting methods: Kuijken 99, Refregier & Bacon 2003, Bernstein & Jarvis 02, Bridle et al 02, Nakijima & Bernstein 07, Miller et al. 07, Peng et al. 02
- Stacking methods: Lewis 09, Hosseini & Bethge 09

→ Data challenges: STEP (Heymans et al. 2005, Massey et al 2006); GREAT 08 (Bridle et al. 08) systematics variance of $\sim 2 \times 10^{-7}$ for constant shear; Current: $\sim 3-8 \times 10^{-6}$
Toy Model

- Fit 2D gaussian to 2D gaussian
- Only one free parameter: size
- Additive gaussian noise
- Convolution with known gaussian PSF

Refregier, Amara, Bridle, Kacprzak, Rowe 2011
Noise Bias

Maximum Likelihood Estimator: \( \chi^2 \)

\[ \delta a_i \simeq -\frac{1}{2} F_{ij} F_{kl} B_{jkl} \propto 1/\text{SNR}^2 \]

\[ F_{ij} = \sum_p \frac{1}{\sigma_p^2} \frac{\partial f}{\partial a_i} \frac{\partial f}{\partial a_j} \]

\[ B_{ijk} = \sum_p \frac{1}{\sigma_p^2} \frac{\partial f}{\partial a_i} \frac{\partial^2 f}{\partial a_j \partial a_k} \]

Refregier, Amara, Bridle, Kacprzak, Rowe 2011

Gal/PSF size = 1.25
Ways Forward

- Use galaxies with higher S/N
- Avoid non-linearities
- Go beyond MLE: Bayesian methods, other averaging scheme
- Multiple exposures
- Calibrate biases with MC simulations \(\text{(Kacprzak et al. 2011)}\)

→ New ideas welcome!
Conclusions

• Cosmic Shear is a unique method to study the Dark Universe

• New large Cosmic Shear surveys will be available soon

• Measurement of Cosmic Shear is challenging: weak signal from very noisy data, deconvolution, large data volume

→ would benefit from new approaches from Machine Learning