Weak Lensing with the Square Kilometre Array

arXiv:1601.03948
arXiv:1601.03947

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51st Rencontres de Moriond
La Thuile
24 March 2016
Cosmology with the SKA

Introduction

- Galaxy surveys
- Weak lensing
- Intensity mapping
  (Session on Friday)
- Ultra-large scales
  (S. Camera talk Friday)

- Epoch of Reionisation

For more SKA Cosmology:
PoS (AASKA14)
KSP Proposals start 2018!
Cosmology with the SKA
Weak Lensing

• Weak lensing will use SKA-MID
• 350-1760 MHz
• ‘Resolution’ of \(~0.1 \text{ arcsec}\)
• SKA1 (~2023)
  – 194 15m dishes
• SKA2 (~2030)
  – ~2000 dishes
  – Longer baselines across Africa
Gravitational Lensing Cosmology

Basic Principle
Gravitational Lensing Cosmology
Weak Lensing Regime

Galaxies randomly distributed

Lensing Shear

Slight alignment (additional ellipticity)
Weak Lensing Cosmology
Cosmology from Shear

• WL observables probe gravitational potential
  – Very good at measuring matter abundance

• Also track how structures grow over cosmic time
  – Split sources into tomographic redshift bins
  – Dark energy equation of state, modified gravity parameters
Big problem in Weak Lensing is systematics
- …easy to dominate over statistical uncertainty on shear estimate

Want exquisite control of ellipticity added by PSF

...and any other systematic you can think of:
- intrinsic galaxy orientations
- non-linear and baryonic effects on the theory power spectrum
- non-linear and baryonic effects on theory halo mass function
- atmospheric distortions
- chromatic aberration
- selection cuts
- primordial non-gaussianity (yes, really!)
- redshift errors
- shape measurement biases (noise bias, model bias)
- etcetera etcetera
Radio Weak Lensing
Cosmology with Radio Weak Lensing

• WL requires high number densities (>1 arcmin$^{-2}$)
  – …of resolved, high redshift sources
  – Wide fields
  – Exquisite control of ellipticity added by PSF

• Previously only really available at optical wavelengths
Radio Weak Lensing
Cosmology with Radio Weak Lensing

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For radio wavelengths a μJy depth, ~$10^3$ deg$^2$, sub-arcsecond survey ‘easy’ using SKA
Radio Weak Lensing
Advantages of Radio Weak Lensing

• Deterministic, precisely known PSF (in principle)
  – No stochastic atmosphere ‘seeing’

• Higher redshift source distribution
  – Appreciable tail above redshift 3 and up to 10

• Extra information on intrinsic alignments
  – HI rotational velocity measurements (e.g. Morales 2005)

• Spectroscopic HI 21 cm line redshifts

• Cross-correlation studies with other wavebands
  – Wavelength dependent systematics drop out!
Radio Weak Lensing
Challenges – Shape Measurement

Gravitational lensing by intervening matter

Observation by interferometer

Deconvolution Process

Cosmological Shear Measurement

$\sigma_{\text{sys}} < 1\%$ for detection

$\sigma_{\text{sys}} < 0.01\%$ for useful cosmology
Radio Weak Lensing

Disadvantages of Radio Weak Lensing

• Radio interferometers not imaging telescopes!
• Data arrives as ‘visibilities’ – poorly sampled 3D Fourier transform of the sky
  – PSF deterministic but significant sidelobes across entire sky
  – All sources are confused!
• Measuring morphology requires deconvolving this PSF or modelling visibilities directly
• See radioGREAT challenge for shear measurement data challenge
  – http://radiogreat.jb.man.ac.uk
SKA Weak Lensing
Survey Optimisation with skalens

• Can observe with SKA using different frequency sub-bands

• How low in $\nu$ can we go?
  ✓ Synchrotron spectrum of sources gives higher $n_{gal}$
  $\times$ Ionosphere becomes highly turbulent and seeing problem comes back!

• Can also trade-off resolution for sensitivity

• And survey area for depth

• Explore the optimisation of these with skalens pipeline

(Bonaldi, IH, Camera, Brown, arXiv:1601.03948)
SKA Weak Lensing
Survey Optimisation with skalens

- Choose experiment configuration from SKA1-MID
  Sensitivity curve (Robert Braun)
- Source catalogues from star-forming galaxy distributions in semi-empirical SKADS sims (Wilman et al 2008)
• Recover observed shear power spectra in 6 redshift bins
• Optimise configuration on:
  – Total shear SNR
  – DETF Figure of Merit (constraint on $w_0 - w_a$)
• ‘Sweet spot’
  – $\sim 1.00$ GHz central $\nu$
  – 0.5 arcsec FWHM
  – 1,000 – 5,000 deg$^2$
SKA Weak Lensing
Forecasts for SKA Surveys

- Also consider MCMC forecasts for SKA1 and SKA2 WL surveys

Map posterior with MultiNest wrapped in COSMOSIS (Zuntz et al 2015)
- Compare to forecasts for optical experiments
- SKA has lower number density, but more sky, higher redshift sources

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$A_{\text{sky}}$ [deg$^2$]</th>
<th>$n_{\text{gal}}$ [arcmin$^{-2}$]</th>
<th>$z_m$</th>
<th>$f_{\text{spec-z}}$</th>
<th>$z_{\text{spec-max}}$</th>
<th>$\sigma_{\text{photo-z}}$</th>
<th>$z_{\text{photo-max}}$</th>
<th>$\sigma_{\text{no-z}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKA1</td>
<td>5,000</td>
<td>2.7</td>
<td>1.1</td>
<td>0.15</td>
<td>0.6</td>
<td>0.05</td>
<td>2.0</td>
<td>0.3</td>
</tr>
<tr>
<td>DES</td>
<td>5,000</td>
<td>12</td>
<td>0.6</td>
<td>0.0</td>
<td>2.0</td>
<td>0.05</td>
<td>2.0</td>
<td>0.3</td>
</tr>
<tr>
<td>SKA2</td>
<td>30,000</td>
<td>10</td>
<td>1.3</td>
<td>0.5</td>
<td>2.0</td>
<td>0.03</td>
<td>2.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Euclid-like</td>
<td>15,000</td>
<td>30</td>
<td>0.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.03</td>
<td>4.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>
For a ‘Stage III’ Survey, SKA1 (2020+) comparable to DES

(IH et al arXiv:1601.03947)
SKA Weak Lensing
SKA Forecasts

- By ‘Stage IV’ SKA2 (~2030) can beat a Euclid-like weak lensing experiment

(IH et al arXiv:1601.03947)
SKA Weak Lensing
SKA Forecasts

• ...and cross-correlations do not significantly degrade statistical precision, but greatly improve robustness to systematics

(IH et al arXiv:1601.03947)
Recently demonstrated in FIRST radio and SDSS optical lensing:

- Imprint systematics
- ... remove by cross-correlation

(Demetrouillas & Brown, 2015)
Radio Weak Lensing

Summary

• SKA can do WL competitive with premier optical surveys… but not just ‘me too’

• Radio can be panacea for many WL systematics
  – Cross correlations!
  – Spec-zs from HI line
  – Polarisation/rotational velocities for Intrinsic Alignments

• Radio weak lensing will be hard
  – shear measurement from interferometer an open question
  – requirements on source classification schemes
  – need to know source of redshift information
Radio x Optical Weak Lensing

Rationale

• For optical and radio shear estimates with wavelength-dependent systematics:

\[ \tilde{\gamma} = \gamma + \gamma^s \]

• These should disappear in the cross-correlation:

\[ \langle \tilde{\gamma}_o \tilde{\gamma}_r \rangle = \langle \gamma \gamma \rangle + \langle \gamma \gamma_o^s \rangle + \langle \gamma \gamma_r^s \rangle + \langle \gamma_o^s \gamma_r^s \rangle \]
Radio x Optical Weak Lensing

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Radio Weak Lensing Survey Timeline
Surveys to Date
VLA FIRST

• Detection of weak lensing in VLA FIRST survey (Chang, Refregier & Helfand 2004)

• Wide but (very) shallow survey
  • 8,000 deg$^2$, ~20 sources deg$^{-2}$

• Measured source shapes directly in UV plane
Current Surveys
SuperCLASS

- Dedicated radio WL survey
  - 1 deg$^2$
  - 0.2 arcsecond resolution
  - 2-3 galaxies arcmin$^{-2}$ in radio
  - Dense supercluster target field
  - ~300 of 800 hours observed so far
- Multiwavelength coverage
  - e-MERLIN and JVLA at 1.4GHz
  - Subaru in optical
  - LOFAR and GMRT at low radio
  - SCUBA-2 in sub-mm
  - Spitzer in NIR
Current Surveys

SuperCLASS

- e-Merlin 1.4GHz
- Achieving ≈17μJy noise
  - expected from data so far
- GMRT 330MHz (Riseley et al)
  - 34μJy/beam rms noise
- SuprimeCam BVRiZ (Caitlin Casey)
  - Completed to 25mag
Future Surveys
V-DECS

- VLA-Deep Extragalactic Cosmology Survey
- Proposed JVLA survey
  - recasting of DEEP component of VLASS
- WL key science driver
  - 10 deg$^2$
  - 0.75 arcsecond resolution
  - 3-4 galaxies arcmin$^{-2}$
  - COSMOS, ELIAS-N1 fields
- High significance detection of shear power spectrum
In terms of linear model of bias on source ellipticity measurement:

\[ e^{obs} = (1 + m)e^{true} + c \]

### Table: Requirements on Systematics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( A_{sky} )</th>
<th>( n_{gal} )</th>
<th>( z_m )</th>
<th>( m &lt; )</th>
<th>( c &lt; )</th>
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</thead>
<tbody>
<tr>
<td>DES</td>
<td>5000</td>
<td>12</td>
<td>0.8</td>
<td>0.004</td>
<td>0.0006</td>
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<tr>
<td>Euclid</td>
<td>20000</td>
<td>35</td>
<td>0.9</td>
<td>0.001</td>
<td>0.0005</td>
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<tr>
<td>SKA1-early</td>
<td>5000</td>
<td>1.2</td>
<td>0.8</td>
<td>0.012</td>
<td>0.0011</td>
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<tr>
<td>SKA1</td>
<td>5000</td>
<td>2.7</td>
<td>1.0</td>
<td>0.0067</td>
<td>0.00082</td>
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<td>SKA2</td>
<td>30940</td>
<td>10</td>
<td>1.3</td>
<td>0.0012</td>
<td>0.00035</td>
</tr>
</tbody>
</table>
Problem 1/N: Shape Measurement
Current Performance

- CLEAN imaging gives poor results with respect to requirements

Patel, IH et al 2015
(SKAI sims, CLEANed images)
Problem 1/N: Shape Measurement
Current Performance

- CLEAN imaging gives poor results with respect to requirements

![Bar chart showing required vs. current performance for different experiments with a log scale for required Q.]

**SKAI requirement**: 0.4

- **Current methods**: 0.4
- **SuperCLASS 2015+**: 800
- **VLASS-DEEP 2016+**: 140
- **SKA1-early 2018+**: SKA1 2024+ 800
- **SKA2 2030+**:
SKA Weak Lensing Survey Optimisation with skalens

- Generate source catalogues from star-forming galaxy distributions in semi-empirical SKADS S3-SEX simulation + data-motivated corrections (Wilman et al 2008)
SKA Weak Lensing
Survey Optimisation with skalens

• …+ data-motivated corrections
SKA Weak Lensing
Survey Optimisation with skalens

- Assign a (noisy) observed shear as function of SNR from IM3SHAPE simulations (Kacprzak)
SKA Weak Lensing
Survey Optimisation with skalens

![Graph showing FoM parameters for SKA surveys.](image-url)
Radio Weak Lensing

Source Redshift Distributions

Galaxy Number Density $dN_{\text{gal}}/dz$ [arcmin$^{-2}$]

- DES
- Euclid–like
- SKA1
- SKA2

Redshift $z$
Radio Weak Lensing
SKA Forecasts

• With Planck Priors:

(IH et al arXiv:1601.03947)
## Radio Weak Lensing
### SKA Forecasts

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$(\sigma_{\Omega_m}/\Omega_m, \sigma_{\sigma_8}/\sigma_8)$</th>
<th>$(\sigma_{w_0}, \sigma_{w_a})$</th>
<th>$(\sigma_{\Sigma_0}/\Sigma_0, \sigma_{Q_0}/Q_0)$</th>
<th>DETF FoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKA1</td>
<td>0.083 0.040</td>
<td>0.36 0.54</td>
<td>0.19 0.43</td>
<td>5.8</td>
</tr>
<tr>
<td>SKA1 + Planck</td>
<td>0.084 0.040</td>
<td>0.28 0.43</td>
<td>- -</td>
<td>77</td>
</tr>
<tr>
<td>DES</td>
<td>0.056 0.032</td>
<td>0.25 0.54</td>
<td>0.13 0.43</td>
<td>9.8</td>
</tr>
<tr>
<td>DES + Planck</td>
<td>0.058 0.033</td>
<td>0.22 0.33</td>
<td>- -</td>
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<tr>
<td>SKA1×DES</td>
<td>0.046 0.024</td>
<td>0.28 0.54</td>
<td>0.13 0.39</td>
<td>8.8</td>
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<tr>
<td>SKA1×DES + Planck</td>
<td>0.046 0.024</td>
<td>0.23 0.36</td>
<td>- -</td>
<td>106</td>
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<tr>
<td>SKA2</td>
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<td>0.14 0.42</td>
<td>0.04 0.13</td>
<td>51</td>
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<tr>
<td>SKA2 + Planck</td>
<td>0.010 0.0047</td>
<td>0.086 0.15</td>
<td>- -</td>
<td>305</td>
</tr>
<tr>
<td>Euclid-like</td>
<td>0.011 0.0058</td>
<td>0.13 0.38</td>
<td>0.053 0.17</td>
<td>54</td>
</tr>
<tr>
<td>Euclid-like + Planck</td>
<td>0.012 0.059</td>
<td>0.095 0.16</td>
<td>- -</td>
<td>244</td>
</tr>
<tr>
<td>SKA2×Euclid-like</td>
<td>0.013 0.0064</td>
<td>0.15 0.43</td>
<td>0.053 0.17</td>
<td>45</td>
</tr>
<tr>
<td>SKA2×Euclid-like + Planck</td>
<td>0.013 0.0064</td>
<td>0.10 0.17</td>
<td>- -</td>
<td>240</td>
</tr>
</tbody>
</table>

(IH et al arXiv:1601.03947)
Radio x Optical Weak Lensing
Cross-Spectra and Shape Covariance

- Observed shear spectra have noise:

\[ \tilde{C}_\ell^{X_i Y_j} = C_\ell^{X_i Y_j} + \mathcal{N}_\ell^{X_i Y_j} \]

- Usual noise term:

\[ \mathcal{N}_\ell^{i j} = \delta^{i j} \frac{\sigma_{g_i}^2}{N_{\text{gal}}^i} \]

- Full one between different experiments:

\[ \mathcal{N}_\ell^{X_i Y_j} = \frac{N^{X_i Y_j}_{\text{gal}}}{N_{\text{gal}}^{X_i} N_{\text{gal}}^{Y_j}} \text{COV}(\epsilon_{X_i}, \epsilon_{Y_j}) \]

- Different wavelengths
- Different redshift bins
Radio x Optical Weak Lensing
Catalogue Matches

(Camera, IH et al in prep.)
Challenges – Shape Measurement
Requirements from SKA

• ‘Bespoke’ imaging methods can’t start from deconvolved images…
• Current SKA continuum and spectral imaging pipelines specify only images as output
• Have written an SKA ECP to request gridded visibilities as an output (IH, Michael Brown ECP1500007)
  – ‘Spigot’ output at correct point in pipeline
• Currently at Change Review Board stage
• Comments and expressions of support welcome!